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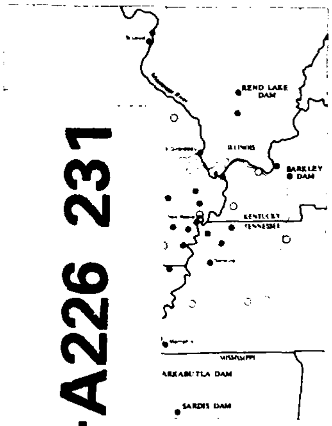
Report 1

EARTHQUAKE RESPONSE SPECTRAL ANALYSIS OF ARKABUTLA DAM, MISSISSIPPI



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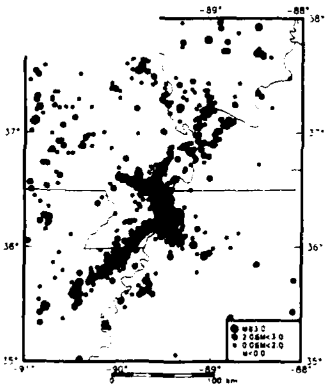

by

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This report provides ~~a~~ permanent documentation for and ~~presents an analysis of~~ the accelerograms for the main shock (m_b = 5.0) and aftershock (m_b = 4.5) of the New Madrid earthquakes of 25 March 1976 obtained at the Arkabutla Dam, Mississippi. Both epicenters occurred in Arkansas at latitude 35.6°N, longitude 90.5°W. The preliminary results of the integration of 12 accelerograms recorded at the Arkabutla Dam were published by Herrmann (1977). The main purposes of this study ~~are~~ is to analyze the response spectra of acceleration, velocity, and displacement, the amplification factors, and the natural periods of foundation, dam, and abutment.

All response spectra of longitudinal (L), vertical (Z), and transverse (T) components for the downstream (toe), crest, and abutment of Arkabutla Dam were

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presented individually. Five percent damped spectral amplitude-ratios of the L-component at the toe to those at the abutment and the similar crest to the abutment rates were 4.2 and 2.2, respectively, at the period of 0.35 sec or 2.9 Hz. Therefore, 0.35 sec is the natural period for both foundation and dam. Evidently, the spectral amplitude of the L-component at 0.35 sec on the crest of the dam was deamplified or reduced directly due to the dissipation (attenuation) of wave energy in the dam. Also, the acoustic impedance of the foundation and the acoustic impedance of the dam were approximately the same. The average amplification factor of the vertical component for the toe relative to the abutment is 3.22 for the period of 0.25 sec or 4 Hz; for the T-component it is 1.06 and 0.93 for 0.35 sec (2.9 Hz) and 0.40 sec (2.5 Hz), respectively.

The natural periods or natural frequencies determined from the observed response spectra of the foundation are 0.35 sec (2.9 Hz), 0.25 sec (4.0 Hz), and 0.38 sec (2.6 Hz) for L-, Z-, and T-components. For the dam, the natural periods are 0.35 sec (2.9 Hz), 0.33 sec (3.0 Hz), and 0.38 sec (2.6 Hz) for L-, Z-, and T-components, and for the right abutment the natural periods are 0.35, 0.35, and 0.38 sec for L-, Z-, and T-components.

PREFACE

The US Army Engineer Waterways Experiment Station (WES) was authorized by the US Army Engineer Division, Lower Mississippi Valley (LMVD), on 23 January 1987 to conduct this study by appropriation order FY 87-IAO No. 4732. Mr. William Milton Myers was the LMVD coordinator.

The study was accomplished and the report written by Mr. Frank K. Chang, Earthquake Engineering and Geophysics Division (EEGD), Geotechnical Laboratory (GL), WES. Unequal interval digitized New Madrid earthquake data of 1975-1976 have been kindly provided by Professor R. B. Herrmann, St. Louis University, and equal interval digitization (0.02 sec) of the same records was provided by the National Geophysical Data Center, National Oceanic and Atmospheric Administration. The shear-wave velocity profiles at Arkabutla Dam site were provided by Mr. Don Yule, EEGD. Mr. Bill Tull, Assistant Task Leader, Computer Science Corporation, plotted the response spectra for this report. The report was edited by Mrs. Joyce H. Walker, Information Management Division, Information Technology Laboratory, WES. The critical reviews and comments were provided by Professor W. D. Liam Finn, University of British Columbia (sabbatical leave 1989 at WES), Dr. P. Hadala, Assistant Chief, and Dr. E. L. Krinitzsky and Mr. R. E. Wahl, GL. Mr. Robert F. Ballard, Jr., was the General Manager of the Strong Motion Instrumentation Program. General supervision was by Dr. A. G. Franklin, Chief, EEGD, GL, and Dr. William F. Marcuson III, Chief, GL.

COL Larry B. Fulton, EN, was Commander and Director of WES during the publication of this report. Dr. Robert W. Whalin was Technical Director.

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ARKABUTLA DAM, MISSISSIPPI

PART I: INTRODUCTION

Background

1. At 18:41:20.5 CST on 24 March 1976 or 00:41:20.5 UT (universal time) on 25 March 1976, an earthquake of $m_b = 5.0$ occurred in Arkansas at latitude 35.6°N, longitude 90.5°W with a focal depth of 12 km. The event had a seismic moment $M_o = 1.2 \times 10^{23}$ dyne cm and corner frequency of 0.7 Hz (Herrmann 1977). An aftershock event of 4.1 on the Richter scale or $m_b = 4.5$ was recorded about 20 min later. It had a focal depth of 14 km, a seismic moment $m_o = 2.5 \times 10^{22}$ dyne cm, and an estimated corner frequency of 0.86 Hz (Herrmann 1977). The latitude, longitude, and origin time were 35.6°N, 90.5°W, and 01:00:11.9 UT, respectively. The main shock was felt over parts of Illinois, Missouri, Kentucky, Tennessee, Arkansas, Mississippi, and Alabama, and had an epicentral intensity of MMI = VI. No damage was reported.

2. Herrmann (1977) reported the fault plane solutions for the main and aftershock events. The main shock had one nodal plane at a strike of 323° and a dip of 63°NE, and the second nodal plane had a strike of 40° and a dip of 65°NW. The first motions of P-waves are right lateral motions on the nodal plane striking 40°. This nodal plane is taken to be the fault plane, because it parallels a 100-km microearthquake trend in the New Madrid seismic zone. The fault plane solution for the aftershock event indicates that one nodal plane had a strike of 45° with a dip of 80°SE and the second nodal plane had a strike of 309° with a dip of 60°NE. The first motion of a P-wave train was in the direction of right lateral faulting on the first nodal plane.

3. The Corps of Engineers strong-motion networks at Arkabutla Dam, Mississippi (99 km from epicenter), and Wappapello Dam, Missouri (150 km), were triggered by the shock. In addition, one accelerograph at Tiptonville, Tennessee (130 km), and another acccelerograph at New Madrid, Missouri (131 km), also recorded the main event. These latter instruments belong to the array of US Geological Survey. The aftershock of $m_b = 4.5$ was recorded by the SMA-1 accelerograph at the toe of Arkabutla Dam only. Accelerographs located at the abutment and crest of Arkabutla Dam did not record the

aftershock due to energy dissipation in the dam and abutment. Figure 1 shows the epicenter and the strong-motion networks of Arkabutla Dam, Sardis Dam, New Madrid, Poplar Bluff, Wappapello Dam, Tiptonville, and Cape Girardeau stations in the New Madrid seismic zone during the main and aftershock events of 25 March 1976.

Purposes

4. The purposes of this report are to analyze the observed spectral response at crest, left toe (freefield downstream), and right abutment of the Arkabutla Dam, and determine the amplification and the apparent resonant or natural periods of the dam and the foundation.

PART II: ARKABUTLA DAM

Description and Geological Environment

5. Arkabutla Lake is located in northwestern Mississippi on the Coldwater River, a tributary of the Yazoo River (Figure 1). The dam is located 6.8 km north of Arkabutla and is one of the flood control dams in the Yazoo River Basin, Mississippi. The dam is of a rolled earthfill, approximately 3,261 m long with a crown width of 12.2 m. Maximum height above the mean valley floor is 20.4 m. The crest elevation is 80.6 m, National Geodetic Vertical Datum (NGVD). It was constructed during the period 1940 to 1943.

6. The dam is founded in a valley filled with alluvium that has an average thickness of approximately 23 m. The alluvium consists of a topstratum of fine-grained sediments (clays, silts, and some fine sands) and a substratum of predominately coarse-grained sediments. The average thicknesses of the topstratum and substratum are about 12 m and 11 m, respectively.

7. Based on the results of seismic field investigations by Mr. Donald Yule including crosshole, downhole, and surface refraction surveys, average shear wave velocities for the foundation in the free field and dam are 183 m/sec (600 ft/sec) and 228.6 m/sec (750 ft/sec), respectively. The average shear wave velocity of the foundation under the dam is about 293 m/sec (960 ft/sec) which is 60 percent higher (Figure 2) than the shear-wave velocity of the foundation in the downstream free field. This difference is probably due to increased effective overburden pressure under the dam and consolidation under the weight of the dam.

Locations of Strong-Motion Instrumentation

8. On 21 May 1973 three SMA-1 accelerographs and seven seismoscopes were installed at the Arkabutla damsite as follows.

Instrument Type	Series Number	Location
SMA-1 and seismoscope	1030 and 206	Right abutment
SMA-1 and seismoscope	1031 and 205	Left toe (freefield downstream)
SMA-1 and seismoscope	1036 and 207	Left crest
Seismoscope	201	Right toe (downstream)
Seismoscope	202	Spillway
Seismoscope	203	Control tower
Seismoscope	204	Right crest

Table 1 shows the characteristics of SMA-1 accelerographs. Figure 3 presents the locations of strong-motion instruments.

Accelerograms and Data Processings

9. The three SMA-1 accelerographs located at the right abutment, the left toe (downstream freefield), and the left crest of Arkabutla Dam were triggered by the main shock (m_b = 5.0) during the eastern Arkansas earthquake of 25 March 1976. The accelerograph (Series No. 1031) at the left toe site was the only one triggered by the aftershock (m_b = 4.5) of 25 March 1976. There were no records for any seismoscopes. Each accelerograph has three components, longitudinal (L), vertical (Z), and transverse (T) with the longitudinal component being oriented in the direction of dam axis. The original uncorrected accelerograms were digitized by Professor R. B. Herrmann, St. Louis University, with funding by the National Science Foundation. The digitized and corrected accelerograms on magnetic tape were obtained from the National Geophysical Data Center, National Oceanic and Atmospheric Administration (NGDC-NOAA). The digitized data interval is 0.02 sec. An unequal interval data tape was also provided by Professor Herrmann. Additional response spectra of L-components at the right abutment, Arkabutla Dam, were plotted from the unequal interval data (see Appendix B) for the purpose of comparison with the equal interval data.

10. The twelve corrected accelerograms (four records) were integrated to obtain corrected velocity and displacement records (Appendix A, after Herrmann 1977). Based on mechanical vibration theory for a one-degree-of-freedom system, a family of absolute acceleration response spectra, relative velocity response spectra, and relative displacement response spectra for damping ratios of 0, 0.02, 0.05, 0.10, and 0.20 were computed and plotted (Figures 4 through 15) using the Nigam and Jennings (1968) computer program.

These spectra provide a description of the period or frequency characteristics of the ground motion and give the maximum response of simple structures to the various components of the earthquake motion.

11. The record lengths of the main shock at Arkabutla Dam were 8, 12, and 22.5 sec for right abutment, left crest, and left toe, respectively. The record length at the toe site was longer; possibly due to the resonant condition of the foundation. The sensitivity of the instrument is also an important factor affecting the record length. The accelerograph located at the crest is a 1-g instrument. The other two located at the toe and the abutment are 1/2-g instruments and are more sensitive; this may have contributed to the longer duration record at the toe also.

Characteristics of Response Spectra

Absolute acceleration response spectrum

12. Figures 4-15 show that the highest peak spectral acceleration is always in the period range (≤ 0.1 sec or ≥ 10 Hz) of compression (P) waves; the secondary peak amplitude is in the period range usually associated with shear (S) waves (0.1 sec $< T < 0.5$ sec; 2 Hz $< f < 10$ Hz). The Rayleigh (R) and Love (L) waves ($t > 0.5$ sec; $f < 2$ Hz) appear as very small peak amplitudes, often not easily recognized in these records. The spectral amplitude approaches zero as the period increases.

Relative velocity response spectrum

13. As in the case of absolute acceleration response, the P-waves usually show the highest spectral amplitudes, though the S-waves contain more energy (Figures 4-15). However, at the resonant period of the S-wave the amplitudes of P and other waves are much smaller. This may be seen in the L-component of the toe (downstream) station (Figure 4), where at the S-wave resonant period of 0.35 sec (2.9 Hz), the shear wave is the largest amplitude on the relative velocity response spectrum. The 0.35-sec period is the natural period of the alluvial deposit at the toe or foundation of the Arkabutla Dam. This resonant period of 0.35 sec appears again on the L-component of the crest recording station (Figure 7). It is noted that the amplification factor of the L-component of the accelerograph on the crest (in relation to the L-component at toe) caused by the height of dam is ≤ 1 (Table 2). The amplitude

of the relative response velocity approaches the base velocity (peak ground velocity) at periods between 1 and 4 sec (Figures 4-15).

Relative displacement response spectrum

14. The R- and L-waves or the long period surface waves are generally the dominant waves in the relative displacement response spectrum except Figure 7. In R-waves, the displacement of the ground surface is partly in the direction of propagation and partly vertical; they will be presented on both radial and vertical components. In L-waves, the displacement is entirely horizontal and at right angles to the direction of propagation. At the resonant periods of the S-waves, the displacement amplitudes of compression and other higher mode S-waves are much smaller, as may be seen in the L-component of the downstream station, where 0.35 sec is the resonant period (Figure 4). However, the long period response of R- and L-waves in the displacement spectrum contain more energy than the S- and P-waves. Woods (1968) show that the wave field generated by a circular footing undergoing vertical oscillations at the surface of a half-space, the Rayleigh wave contains 67 percent of total energy; shear wave 26 percent, and compression wave 7 percent. Woods' findings seem also in agreement with the relative response spectra in this study.

Damping ratios and undamped periods of the response spectra

15. The response spectra for 0-, 2-, 5-, 10-, and 20-percent-critical damping are usually computed and plotted for absolute acceleration, relative velocity, and relative displacement spectra respectively, (Figures 4-15). When the damping value increases, the maximum amplitude and irregularity of the response spectrum will decrease. Thus, the numbers of peaks are reduced. However, the large amplitudes of the predominant periods will be preserved. Usually, the five peaks on the five spectra are almost at the same period, especially the resonant amplitude. This is a very important criterion for searching the natural period of the structure. Sometimes, the fundamental period increases with the increase in damping. Damping actually functions as a low-pass filter, filtering out some or all of the high-frequency responses. In soils, the amount of damping is dependent upon the intensity of ground shaking so that the material damping increases with an increase in ground shaking intensity. At 20 percent damping, which for a concrete structure is usually associated with unacceptable damage, spectra have very few peaks.

PART III: RESULTS AND DISCUSSIONS

Results

16. The corrected maximum acceleration a, maximum velocity v, maximum displacement d, (see definition in discussion) and the ratio of v/a, $a \times d/v^2$, $(v/a)_{vert}/(v/a)_{hori}$, a_{vert}/a_{hori} are listed in Table 2. The parameters of a, v, d, and spectrum intensity SI can be used to establish the attenuation law for the New Madrid seismic zone using the strong motion data from other stations, such as Wappapello Dam (150 km), New Madrid, Missouri (131 km), Tiptonville, Tennessee (130 km). The ratio relationships between a, v, and d can also be studied and compared with the results of other earthquake regions in the world, when more earthquake data might be obtained in the New Madrid seismic region.

17. Table 3 presents an analysis of peaks from the single-degree-of-freedom response spectra for 5 percent critical damping and the ground motion recorded at Arkabutla Dam. The peak spectral amplitudes and the corresponding periods of L, Z, and T components of the acceleration, velocity, and displacement response spectra were selected, and the corresponding amplitude ratios of central crest to right abutment response, central crest to downstream response, and downstream to right abutment response were then determined.

18. In Table 3, the spectral peak periods weie picked based on (a) the large peaks at the predominant periods showing on the spectra of absolute acceleration, relative velocity, and relative displacement; (b) all five peaks of 0-, 2-, 5-, 10-, and 20-percent damping spectra are almost in phase--for example: In Column II of the L-component, the numerical values of four peak periods of 0.07, 0.15, 0.34, and 0.40 sec, at the right abutment shown in Figure 10 were picked; however, two predominant periods of 0.34 and 0.07 sec at the toe (Column IV), and three predominant periods of 0.07, 0.15 and 0.34 sec at the crest (Column V) were picked. The peak numerical values in Columns III, IV, and V are not in parentheses; the numerical values in parentheses are only for the purpose of comparison because they are not the peak values.

Discussions

Spectrum intensity (SI)

19. The SI is the area under the relative velocity spectrum curve for 5 percent critical damping, between the 0 and 4.0 sec periods, or

$$(SI)_{\zeta = 5\ \text{percent}} = \int_{0}^{4.0\ \text{sec}} Sv(\zeta,\ t)\ dt$$

where

- Sv = the amplitude of the relative velocity spectrum
- ζ = the amount of damping
- t = the period (sec)

In this report, $\zeta = 5$ percent. The area under a curve is a measure of the intensity of the ground motion for the range of periods and that amount of damping.

20. The SI's based on the above definition were calculated and listed in Table 2. The SI ratios and peak ground velocity (PGV) of crest/abutment, crest/downstream (d.s.) and downstream/abutment of the L, Z, and T components are presented below for the purpose of comparison:

	Crest/Abutment		Crest/Downstream		Downstream/ Abutment	
Component	SI	PGV	SI	PGV	SI	PGV
L	1.42	1.20	0.61	0.51	2.30	2.35
Z	1.23	1.43	1.05	0.97	1.17	1.46
T	1.01	1.57	0.50	0.71	2.00	2.21

By definition, SI represents the energy of ground shaking. PGV is also representative of the energy of ground motion. Generally speaking, peak amplitude ratios for PGV and the area ratios for SI are of the same order. It is interesting to note that the energy of Z-component on the crest is almost the same as at the toe, i.e., the ratio of crest/downstream ≈ 1. It means there is no energy attenuation of Z-component, however there is at attenuation of energy for both horizontal components.

Natural periods of the foundation and dam from the observed spectra

21. Based on the last column, VIII of Table 3, the spectral amplitude ratios (amplification factors) for downstream/abutment, for the L-component are 4.064, 4.376, 4.085 for a , v , d at the period of 0.35 sec (2.9 Hz); the ratios for crest/abutment (Column VI) are 2.157, 2.418, 2.149 for a , v , d at 0.35 sec (2.9 Hz). In other words, the average amplification factor of downstream/abutment at the period of 0.35 sec (2.9 Hz) in the L-component is 4.2; the average amplification factor of crest/abutment at 0.35 sec (2.9 Hz) for the L-component is 2.2. Natural periods of both the foundation and the dam for the L-component are 0.35 sec (2.9 Hz) (Figure 4). The five peaks of 0.35 sec or 2.9 Hz for the 0, 2, 5, 10 and 20 percent damping response spectra indicated in Figure 4 are all in phase. The average spectral amplitude ratio of a , v , and d at the period of 0.25 sec for the downstream to the abutment of the Z-component is 3.2. The natural period of the vertical component of the foundation is 0.25 sec (4 Hz) (Figure 5). The 0.35 sec (2.9-Hz) spectral peak of the T-component is not as sharp as in the L-component due to the disturbance of other frequencies, but it is in there (Figure 6).

22. The response spectra of L-component at the left crest of Arkabutla Dam indicate the same sharp peak at the period of 0.35 sec (2.9 Hz) as on the L-component at the left toe, but its amplitude has been reduced 47 percent (Figure 7). This is generally in agreement with the reduction of spectral intensities of the L- and T-components (see paragraph 19). The reduction in spectral amplitudes at the crest were directly due to the dissipation of energy in the material of the dam and indirectly due to the very small difference in acoustic impedances across the boundary between the dam and the foundation (Figure 2). A strong peak of 0.336 sec (3.0 Hz) shows on the response spectra of the Z-component (Figure 8). Figure 9 indicates that 0.385 sec (2.6 Hz) becomes a sharp peak in the response spectra of the shear waves of the T-component. Therefore, the observed natural periods of the dam are 0.35 sec (2.9 Hz) 0.336 sec (3.0 Hz), and 0.385 sec (2.6 Hz) for L-, Z-, and T-components.

23. At the right abutment, a predominant period of 0.35 sec (2.9 Hz) is indicated in the response spectra of L- and Z-components (Figures 10 and 11). The five peaks of 0.385 sec (2.6 Hz) for 0, 2, 5, 10 and 20 percent damping

curves of the T-component are all in phase (Figure 12). In conclusion, the natural periods of L-, Z-, and T-components at the right abutment are 0.35 sec (2.9 Hz), 0.35 sec (2.9 Hz) and 0.385 sec (2.6 Hz). The response spectra of L-component were also plotted from the digital data with an unequal data intervals. For the purpose of comparison, they are displayed in Appendix B. The latter shows more detail information than the former.

24. Figures 13, 14, and 15 are the plots of response spectra of L-, Z-, and T-components at the toe of Arkabutla Dam for the aftershock of $m_b = 4.5$ on 25 March 1976. The natural periods of the foundation are 0.35 sec (2.9 Hz), 0.25 sec (4.0 Hz), and 0.35 sec (2.9 Hz) shown on L-, Z-, and T-components, respectively. These are in agreement with the main shock. This aftershock did not trigger the accelerograph on the crest; it means that the ground motion was not amplified by the height of this dam. Inversely, the amplitude was reduced due to the dissipation of energy as discussed for the main shock. Also, the average shear-wave velocities in the 30 ft (10 m) at the bottom of the dam and in the upper 30 ft of the foundation were the same (Figure 2). So, the ratio of the acoustic impedences at the boundary between the dam and the foundation approaches to 1. The impedence is defined as the density times the wave velocity of the layer.

Natural periods of the
foundation and dam from calculation

25. The natural period of the foundation (T_f) could be determined by the equation, $T_f = 4H/V_s$, H = 23 m depth of the foundation, and V_s = average shear wave velocity of the foundation-material. The estimated average shear wave velocities directly under the dam and at the downstream free-field from Figure 2, are 293 m/sec and 183 m/sec, respectively. Therefore, the T_f , directly under the dam, and at the free-field, are 0.31 sec and 0.50 sec. However, the observed natural period from both main shock and aftershock, T_f , is 0.35 sec for L- and T-components at the toe site.

26. The fundamental period (T_1) of a dam-layer system can be represented by the following equation (Sarma 1979)

$$T_1 = \frac{2\pi\, h_1}{\bar{a}_1\, S_1} \qquad (1)$$

where h_1 is the height of the dam, S_1, the shear wave velocity of the material of the dam, and $\bar{a}_1$, is the 1st root of the equation

$$M \tan(q\,\bar{a}_n) = \frac{J_0(\bar{a}_n)}{J_1(\bar{a}_n)} \tag{2}$$

$$M = \frac{\rho_1 S_1}{\rho_2 S_2}, \qquad q = \frac{S_1 h_2}{S_2 h_1} \tag{3}$$

where ρ_1, ρ_2 are the mass densities of the dam and the foundation, respectively, and S_2, h_2 are the shear wave velocity and depth of the foundation. Figure 16 gives the values of $\bar{a}_1$, for a combination of values of M and q. When $\bar{a}_1$, is known, the fundamental period of the dam-layer system can be determined by Equation (1).

27. The parameters of S_1, h_1, S_2 and h_2 have been given as 226 m/sec, 20 m, 293 m/sec, and 23 m in the previous paragraphs. We assume $\rho_1 = \rho_2$, since the materials of the dam and foundation are similar. Therefore,

$$M = \frac{\rho_1 S_1}{\rho_2 S_2} = \frac{226}{293} = 0.77$$

$$q = \frac{S_1 h_2}{S_2 h_1} = \frac{226 \times 23}{293 \times 20} = \frac{5198}{5860} = 0.88$$

Then $\bar{a}_1 = 1.2$ can be determined from Figure 16 and substituted it to Equation (1). We found that the fundamental period of the Arkabutla Dam-layer system

$$T_1 = \frac{6.28 \times 20}{1.2 \times 293} = 0.35 \text{ sec}$$

This is an excellent agreement between the observed and calculated fundamental period of the dam-layer system. The predominant periods of the response spectra of acceleration, velocity, and displacement of L- and Z-components (Figures 7 and 8) are all showing 0.35 sec.

28. Based on the results of this study, it is shown that the fundamental period for the Arkabutla Dam-layer system is 0.35 sec and that this is also the fundamental period for the abutment and the downstream free-field.

PART IV: CONCLUSIONS

29. The average amplification factors of the L-component between the toe and the abutment and the crest and the abutment of the Arkabutla Dam were 4.2 and 2.2 at a frequency of 0.35 sec (2.9 Hz), respectively. The average amplification factor of 2.9 Hz of the L-component for the crest to the toe was 0.54 which is about 46 percent for the spectral amplitude at the crest less than the spectral amplitude at the toe. The average amplification factor of the vertical component for the toe to the abutment is 3.22 for a period of 0.25 sec (4 Hz); T-component is 1.06 and 0.93 for 0.35 sec (2.9 Hz) and 0.40 sec (2.5 Hz), respectively.

30. The natural periods determined from the observed response spectra of the free field are 0.35 sec (2.9 Hz), 0.25 sec (4.0 Hz), and 0.385 sec (2.6 Hz) for L-, Z-, and T-components, respectively. For the dam, the natural periods are 0.35 sec (2.9 Hz), 0.336 sec (3.0 Hz) and 0.385 sec (2.6 Hz) for the L-, Z-, and T-components, and for the right abutment, the natural periods are 0.35 sec, 0.35 sec and 0.385 sec for the L-, Z-, and T-components.

31. By using the Sarma's method of analysis of a dam-layer system, the calculated natural period, 0.35 sec is in agreement with the observed data.

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Table 1

Instrument Characteristics of Arkabutla Dam for the New Madrid Earthquake, 24 March 1976, 18:41:20.5 CST, 25 March 1976, 00:41:20.5 GMT (UT)

Coordinates	Type and Serial No.	Station Location	Component Direction	Period T_o, sec	Sensitivity cm/g	Damping Percent Critical	Starter Sensitivity g
34.76N	SMA-1	2513 Left toe	S-28-W	0.052	3.75	59.0	0.01
90.12W	1031		V-Down	0.052	3.77	59.0	
			S-62-E	0.052	3.75	59.0	
34.72N	SMA-1	2514 Right abutment	S-28-W	0.052	3.95	59.0	0.01
90.12W	1030		V-Down	0.052	4.14	59.0	
			S-62-E	0.052	3.65	59.0	
	SMA-1	2512 Left crest	S-28-W	0.038	1.85	59.0	0.01
	1036		V-Down	0.038	1.85	59.0	
			S-62-E	0.038	1.86	59.0	

Notes:

Static Magnification, $V_s = \omega_n^2 \cdot (\text{Sensitivity}) = \left[\frac{2\pi}{T_o(\text{sec})}\right]^2 \cdot \frac{\text{Sensitivity (cm/g)}}{980\ (\text{cm/sec}^2/\text{g})}$

Periods, sensitivities, and damping values are obtained from the regularly updated listing of Strong-Motion Station Instrumental Data.

Damping ratio, $\varepsilon = \exp\left\{\pi n/\sqrt{(1-n^2)}\right\}$, where n is the fraction of critical damping.

The component direction is that of pendulum motion for the trace to be deflected "upwards" on the record, as described in the notes.

Table 2

Analysis of Strong-Motion Data of Arkabutla Dam

Date	Station	Identification	Comp	Corrected a_{max} cm/sec^2	Corrected v_{max} cm/sec	Corrected d_{max} cm	Spectrum Intensity 5%, ζ	$\frac{a \times d}{v^2}$ Hori	$\frac{a \times d}{v^2}$ Vert	$\frac{v}{a}$ Hori	$\frac{v}{a}$ Vert	$\frac{(v/a)\ vert}{(v/a)\ hori}$	$\frac{a_{vert}}{a_{hori}}$
25 Mar 76	2513	Arkabutla Dam, MS	L S28W	41.10	2.07	0.19	8.52	1.822		0.0504		0.845	0.234
0041 UT		Left toe	Z DOWN	9.63	0.41	0.08	2.00		4.58		0.0426		
M_b = 5.0		Ep. Dist. = 99 km	T S62E	20.17	1.15	0.16	5.48	2.440		0.0570		0.747	0.477
	2512	Arkabutla Dam, MS	L S28W	20.62	1.06	0.14	5.23	2.569		0.0514		1.403	0.269
		Left crest	Z DOWN	5.55	0.40	0.10	2.10		3.47		0.0721		
		Ep. Dist. = 99 km	T S62E	9.76	0.82	0.25	2.76	3.628		0.0840		0.858	0.568
	2514	Arkabutla Dam, MS	L S28W	11.09	0.88	0.17	3.68	2.434		0.0793		0.594	0.535
		Right abutment	Z DOWN	5.94	0.28	0.10	1.70		7.57		0.0471		
		Ep. Dist. = 99 km	T S62E	10.70	0.52	0.05	2.73	1.978		0.0486		0.969	0.555
25 Mar 76	2513	Arkabutla Dam, MS	L S28W	9.46	0.46	0.04	2.21	1.788		0.0486		0.932	0.373
0100 UT		Left toe	Z DOWN	3.53	0.16	0.04	0.67		5.51		0.0453		
M_b = 4.5		Ep. Dist. = 99 km	T S62E	5.27	0.23	0.05	1.40	4.981		0.0436		1.039	0.669

Notes:
EP. Dist. = Epicentral Distance.
Hori = Horizontal.
Vert = Vertical.

Table 3

Analyses of Peaks in 5 Percent Damped Single-Degree-of-Freedom Responses Spectra for the Arkabutla Dam

New Madrid Earthquake of 25 March 1976

I	II		III			IV			V			VI			VII			VIII		
	*Peak		Right Abutment			Downstream (Toe)			Left Center Crest			Amplification Factor Ctr Crest/Rt Abutment			Ctr Crest/Downstream			Downstream/Rt Abutment		
Instrument Component	Period sec	Frequency Hz	a cm/sec^2	v cm/sec	d cm	a cm/sec^2	v cm/sec	d cm	a cm/sec^2	v cm/sec	d cm	a	v	d	a	v	d	a	v	d
L	0.07	14.3	16.818	0.113	0.002	45.920	0.165	0.005	22.130	0.072	0.002	1.316	0.637	1.000	0.482	0.436	0.400	2.730	1.460	2.500
	0.149	6.7	41.557	0.994	0.023	(80.130	1.246	0.046)	42.341	0.718	0.024	1.018	0.722	1.043	(0.528	0.576	0.521)	(1.928	1.253	2.000)
	0.35	2.9	30.497	1.616	0.094	123.955	7.073	0.384	65.797	3.908	0.202	2.157	2.418	2.149	0.531	0.552	0.526	4.064	4.376	4.085
	0.40	2.5	24.500	1.830	0.100	(82.348	5.701	0.329)	(45.451	3.244	0.184)	(1.855	1.773	1.840)	(0.552	0.576	0.559)	(3.361	3.115	3.290)
Z	0.085	11.8	**(15.271	0.174	0.002)	20.323	0.197	0.004	12.976	0.128	0.002	(0.849	0.735	1.000)	0.638	0.649	0.500	(1.331	1.132	2.000)
	0.095	10.5	(24.187	0.327	0.005)	17.218	0.213	0.004	17.183	0.226	0.004	(0.710	0.691	0.800)	0.998	1.061	1.000	(0.712	3.651	0.800)
	0.100	10.0	26.281	0.368	0.007	(13.958	0.185	0.004)	16.954	0.254	0.004	0.645	0.690	0.571	(.214	1.373	1.000)	(0.531	0.503	0.571)
	0.250	4.0	(11.616	0.412	0.018)	36.730	1.345	0.058	16.567	0.587	0.026	(1.426	1.424	1.444)	0.451	0.436	0.448	(3.162	3.264	3.222)
	0.350	2.9	15.938	0.967	0.049	(15.289	1.080	0.047)	13.199	0.777	0.041	0.828	0.830	0.836	(0.863	0.719	0.872)	(0.959	1.117	0.959)
	0.909	1.1	2.102	0.538	0.043	2.005	0.452	0.041	(3.157	0.533	0.088)	(1.502	0.990	0.953)	(1.574	1.179	2.146)	0.954	0.840	0.953
T	0.083	12.1	19.571	0.150	0.003	46.776	0.438	0.008	(13.245	0.092	0.002)	(0.676	0.613	0.666)	(0.283	0.210	0.250)	2.390	2.920	2.666
	0.149	6.7	31.812	0.704	0.018	66.506	1.409	0.038	23.354	0.447	0.013	0.734	0.635	0.722	0.351	0.317	0.342	2.090	2.001	2.111
	0.400	2.5	29.600	1.900	0.118	(26.562	1.898	0.107)	29.348	1.928	0.118	0.991	1.014	1.000	(1.481	1.016	1.103)	(0.897	0.999	0.907)
	0.350	2.9	35.816	1.893	0.111	35.362	2.296	0.109	(21.450	1.146	0.066)	(0.599	0.605	0.594)	(0.606	0.499	0.605)	0.987	1.213	0.982

* These peak periods were picked due to the five peaks of the five response spectra of 0-, 2-, 5-, 10-, and 20-percent damping in phase.

** The numerical values in parentheses were not the maximum values, but for comparison only.

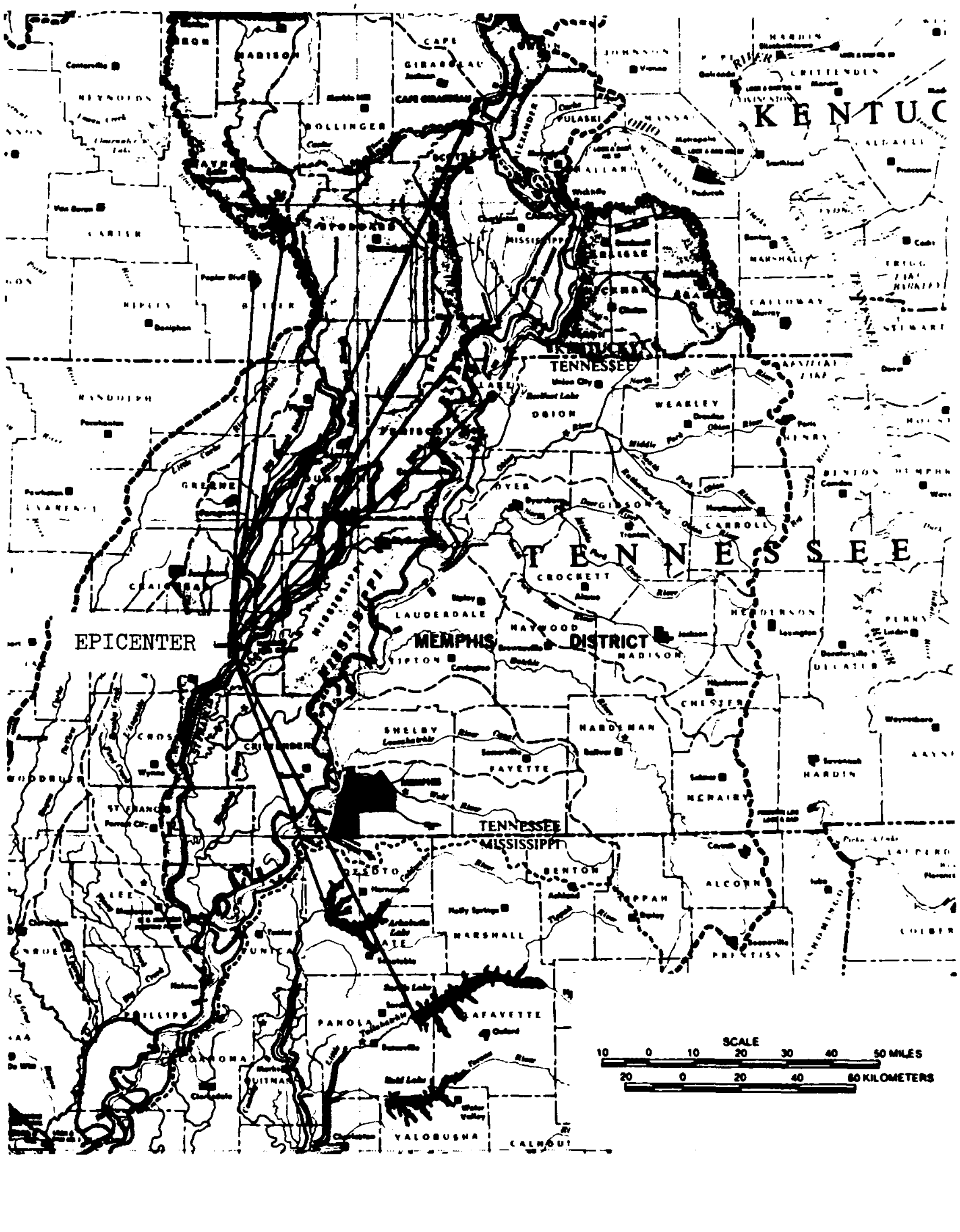


Figure 1. Locations of epicenter and strong-motion stations in the New Madrid Seismic Zone during the earthquakes of 25 March 1976

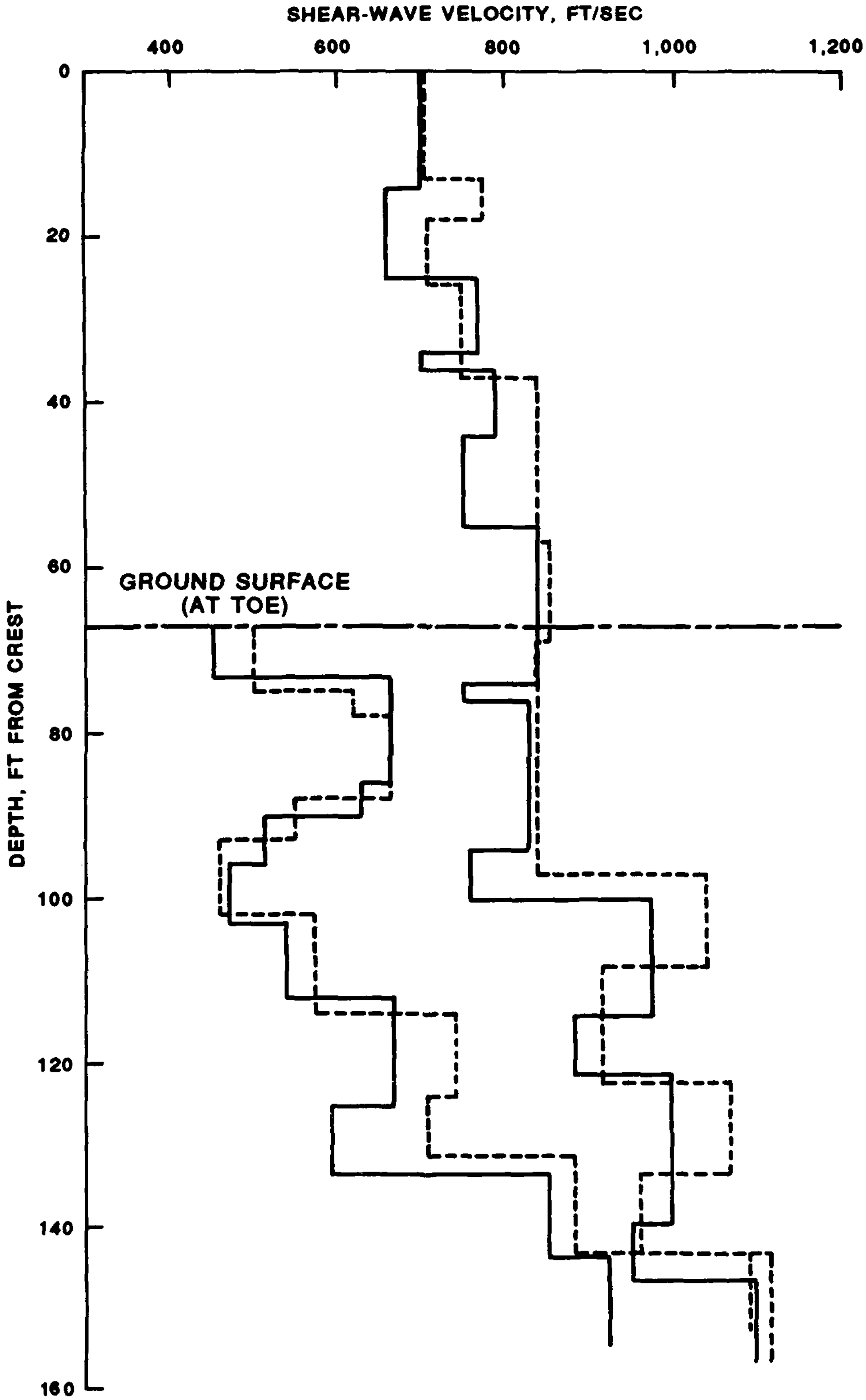


Figure 2. Profile of shear-wave velocity of the Arkabutla Dam and foundation

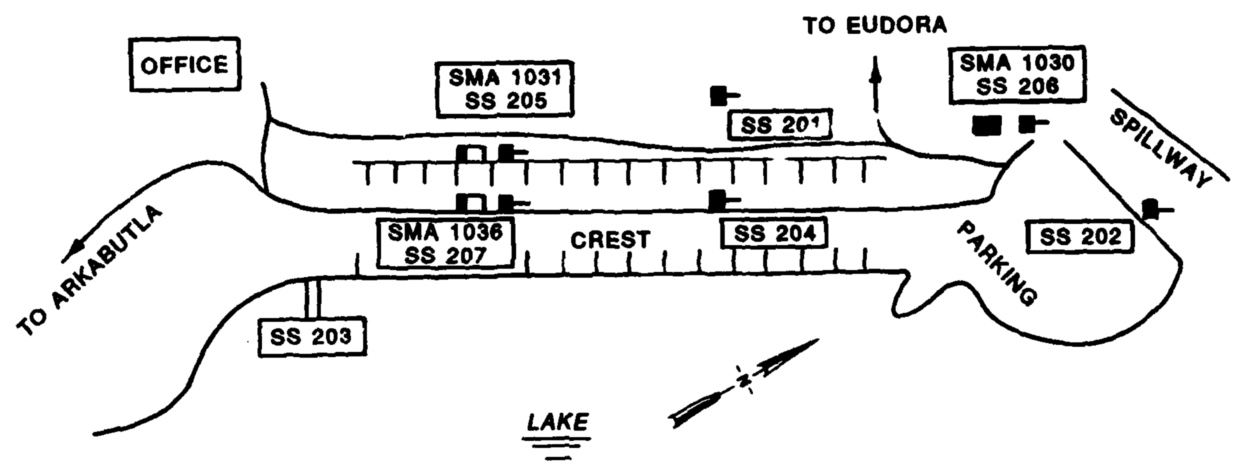


Figure 3. Locations of strong-motion instruments of the Arkabutla Dam

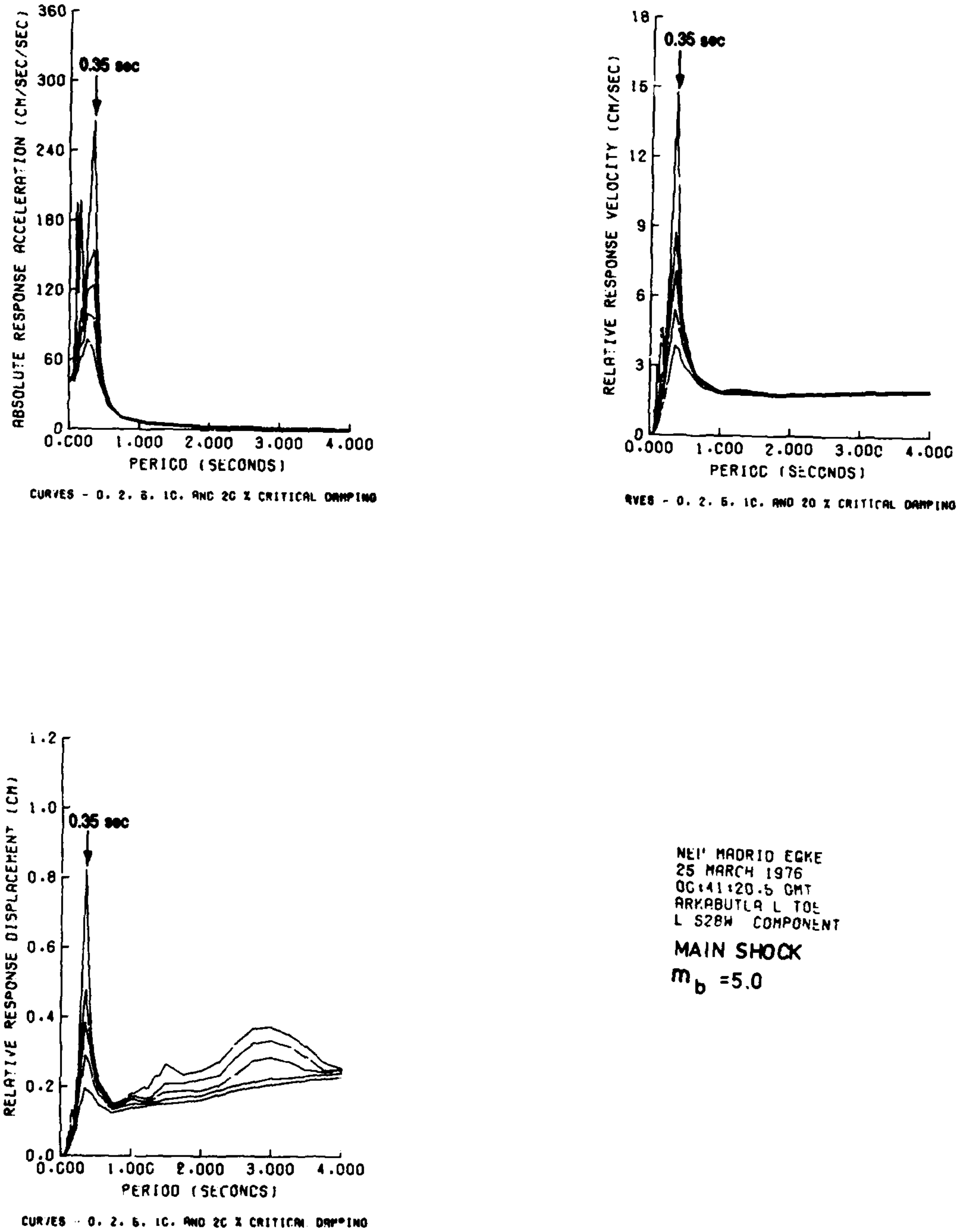


Figure 4. Response spectra of L-component at the toe of Arkabutla Dam

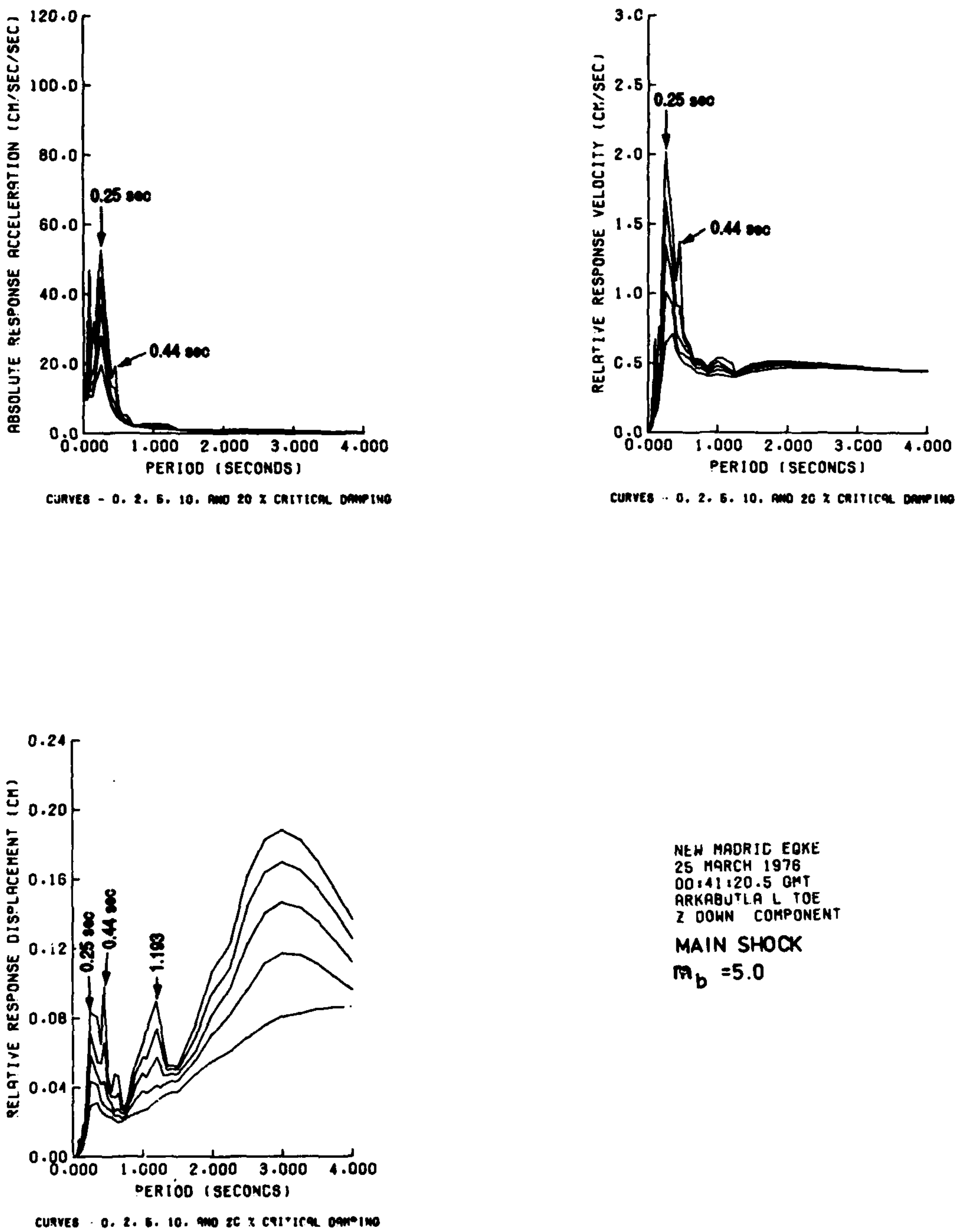


Figure 5. Response spectra of Z-component at the toe of Arkabutla Dam

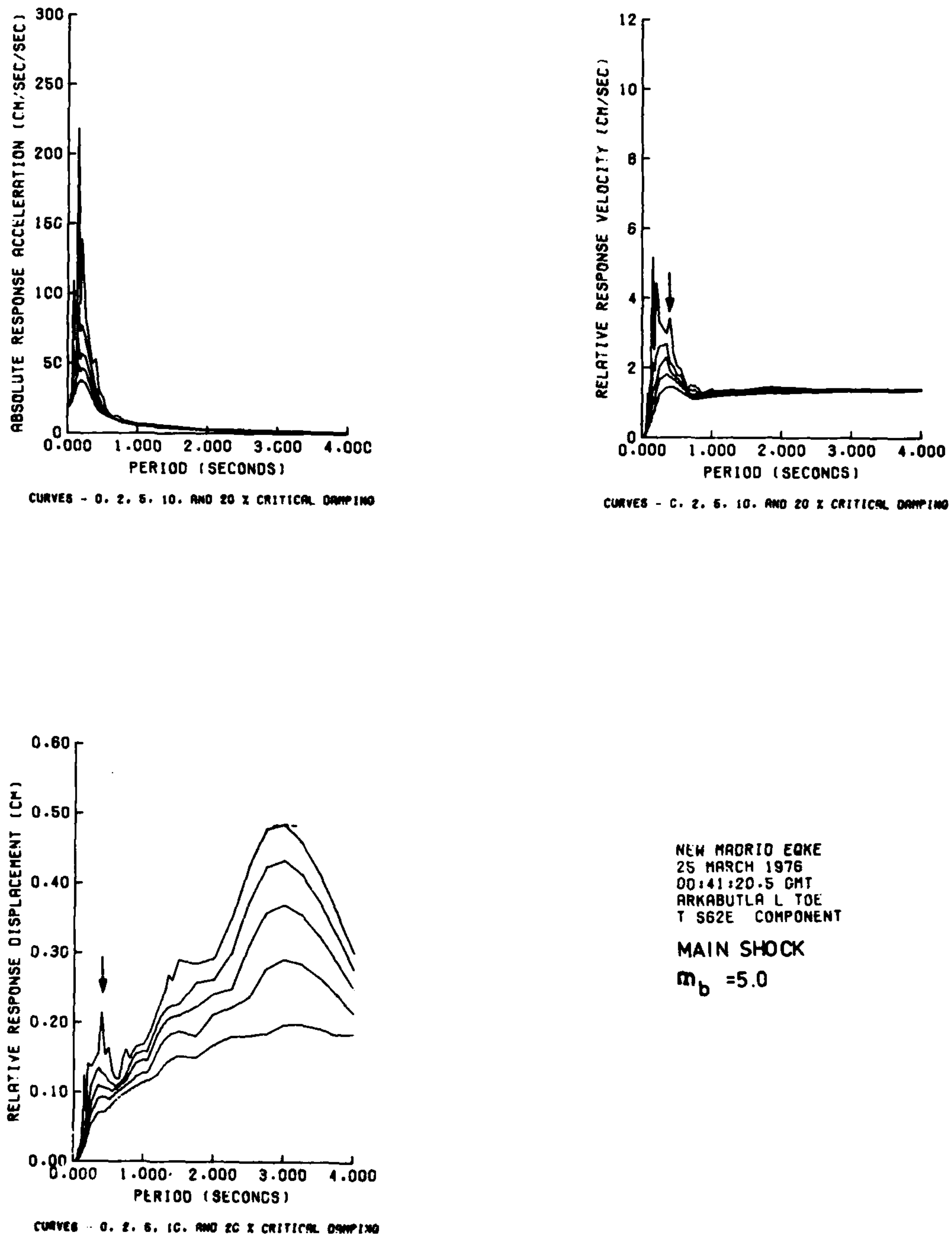


Figure 6. Response spectra of T-component at the toe of Arkabutla Dam

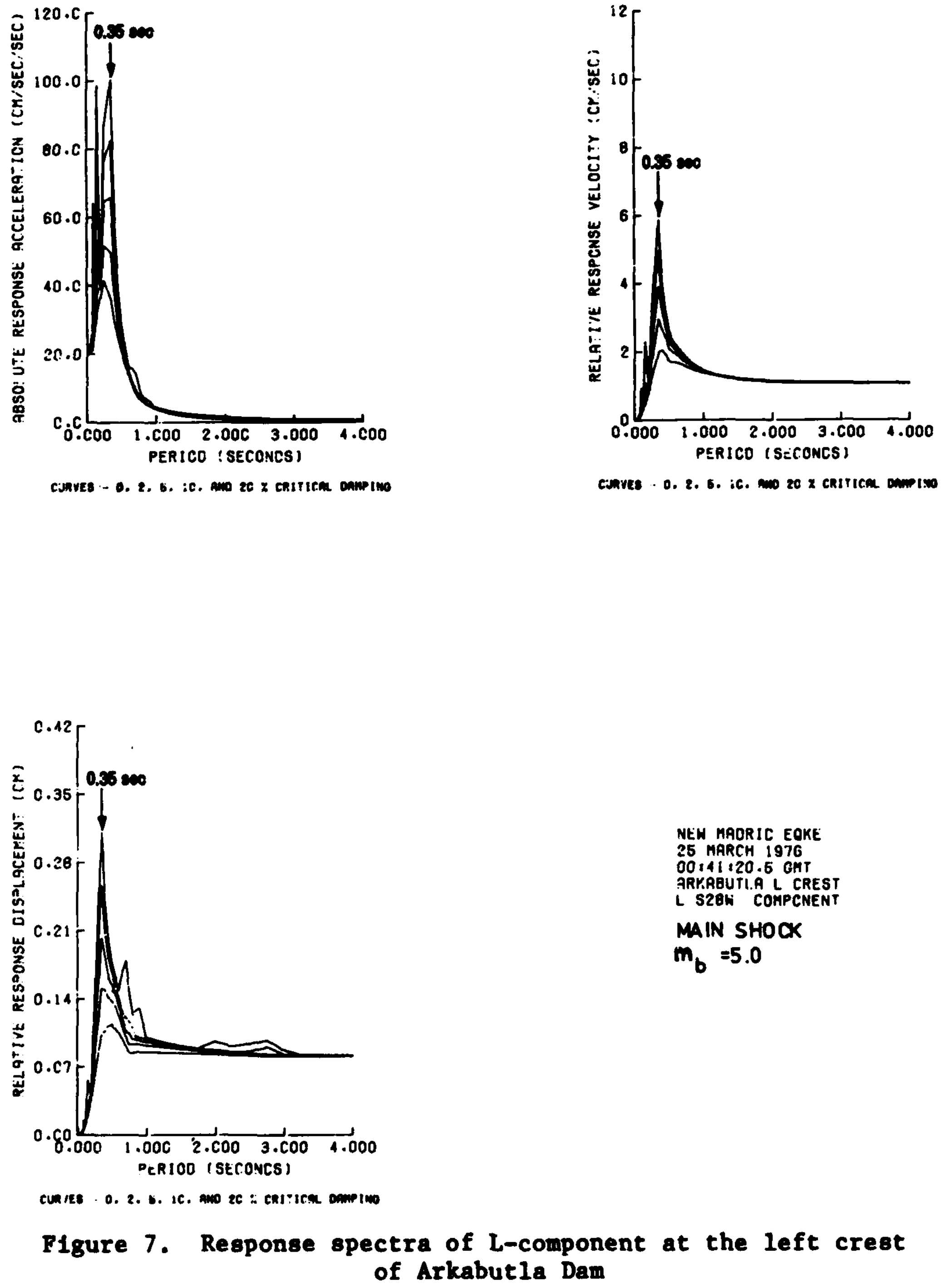


Figure 7. Response spectra of L-component at the left crest of Arkabutla Dam

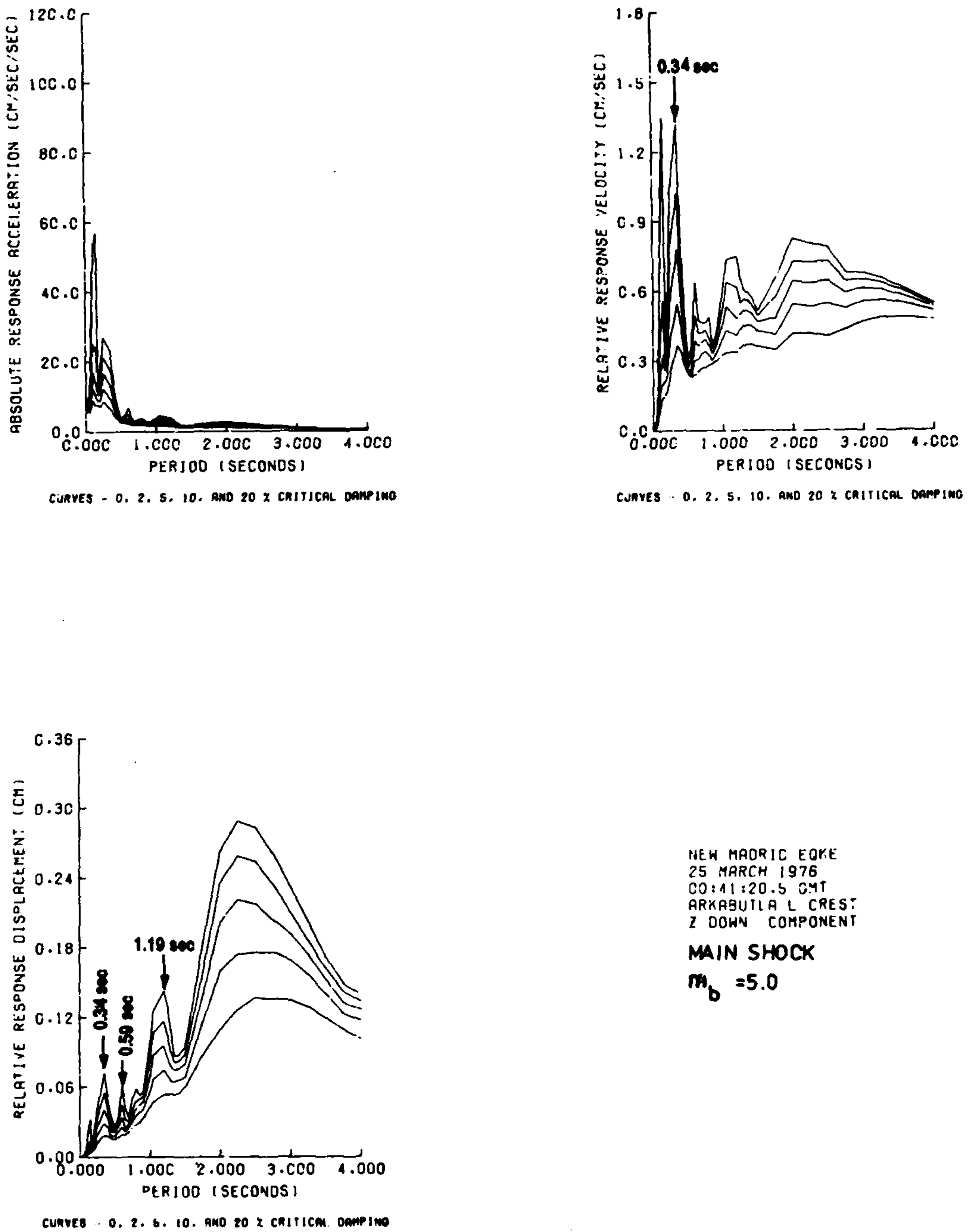


Figure 8. Response spectra of Z-component at the left crest of Arkabutla Dam

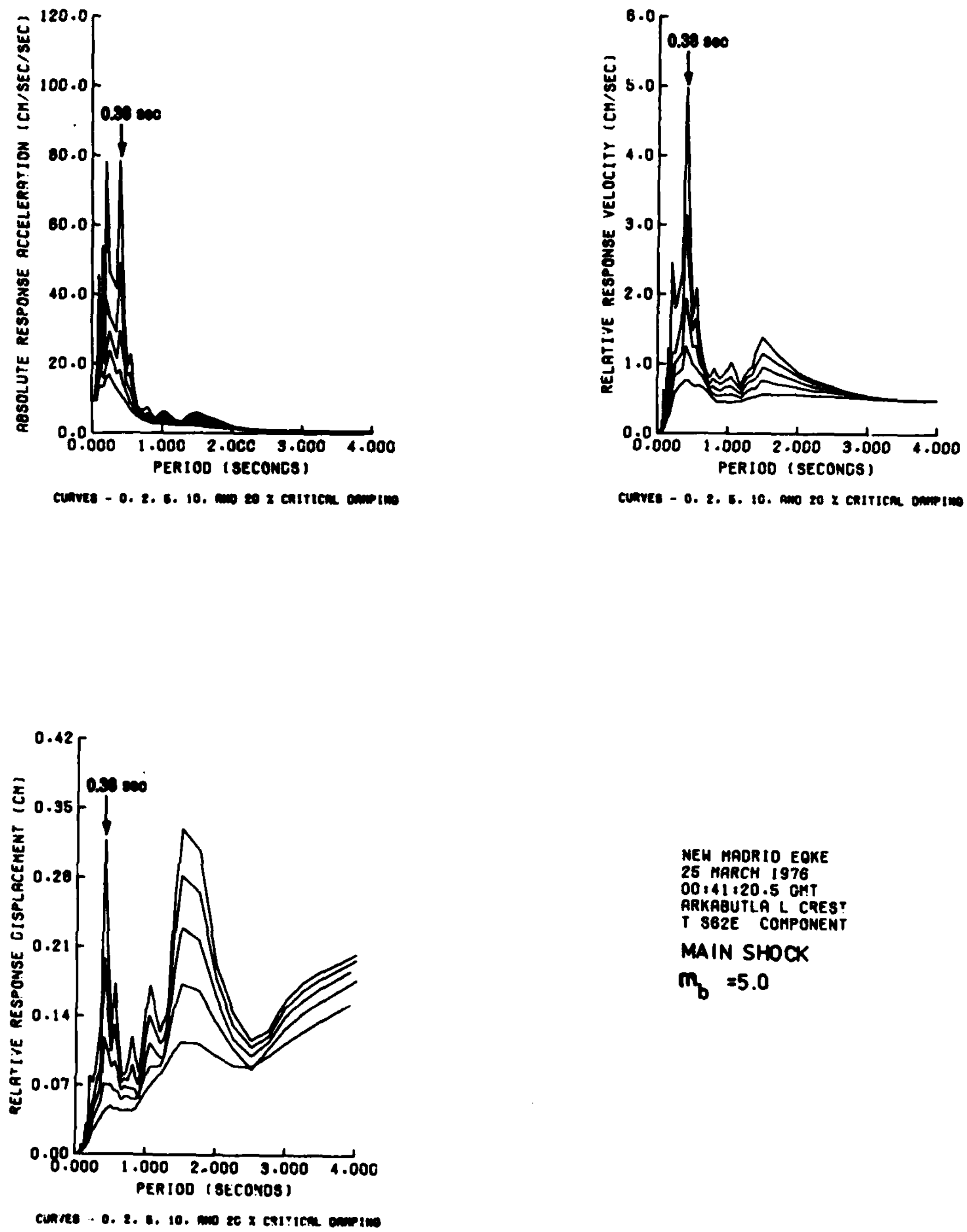


Figure 9. Response spectra of T-component at the left crest of Arkabutla Dam

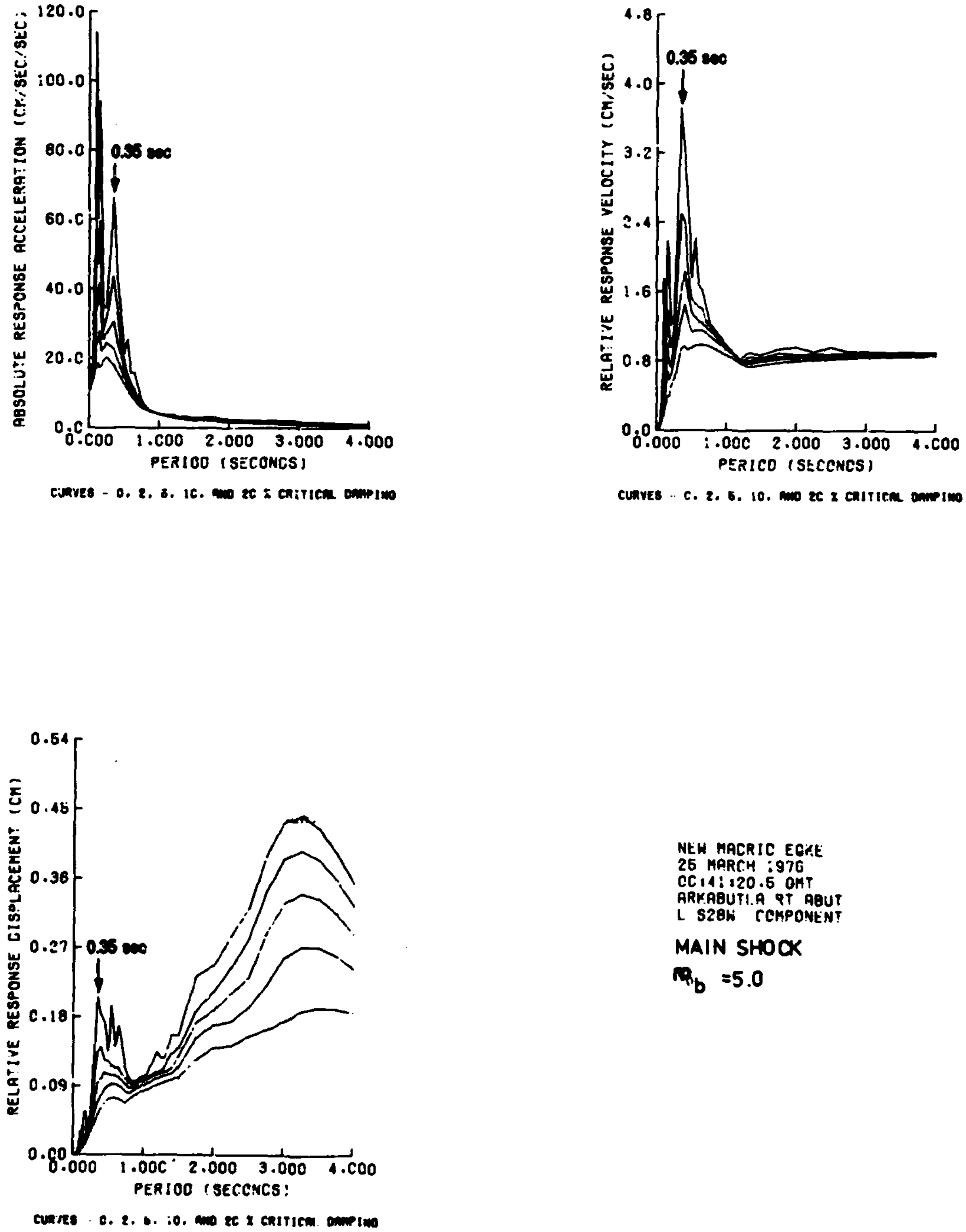


Figure 10. Response spectra of L-component at the abutment of Arkabutla Dam

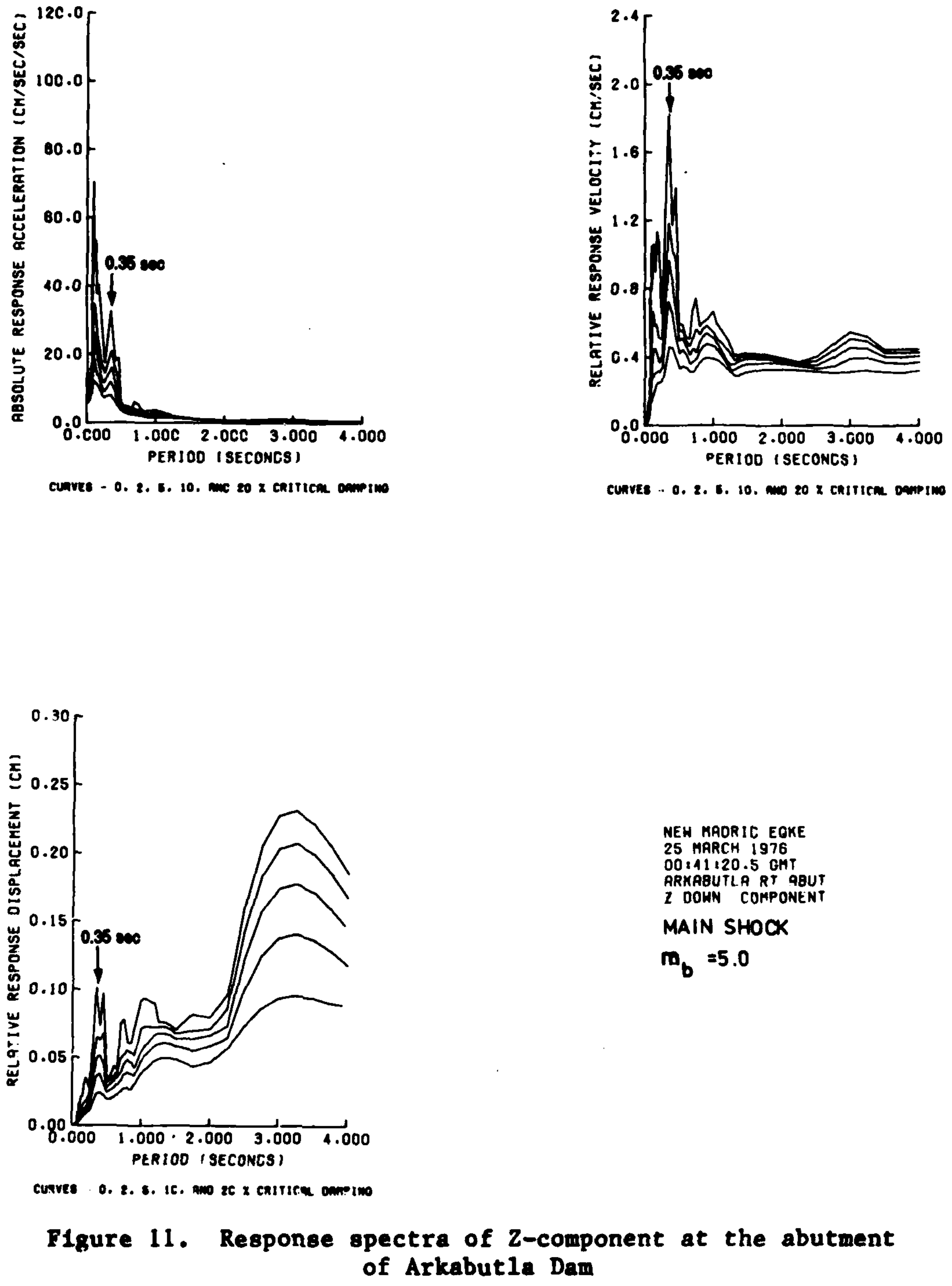


Figure 11. Response spectra of Z-component at the abutment of Arkabutla Dam

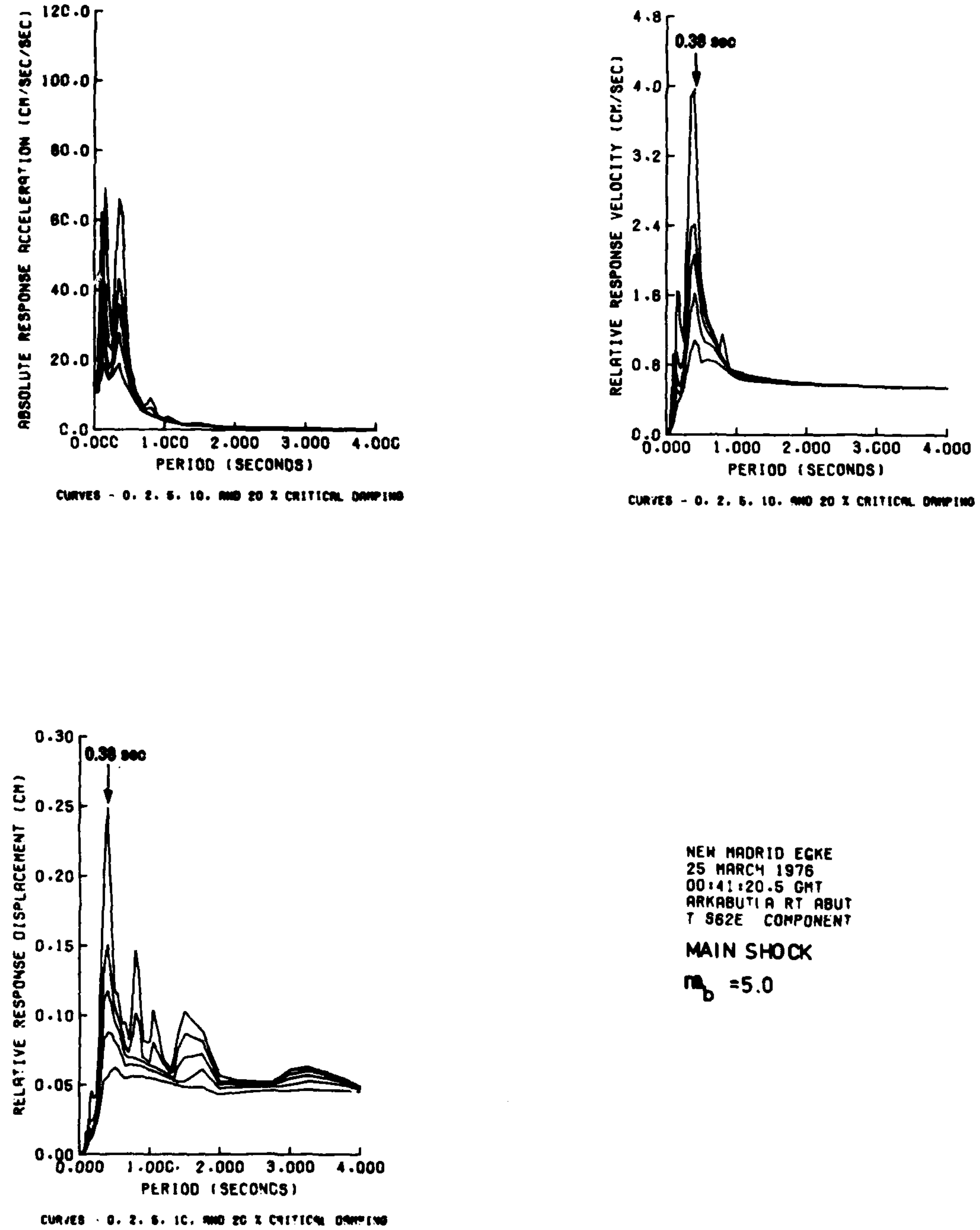


Figure 12. Response spectra of T-component at the abutment of Arkabutla Dam

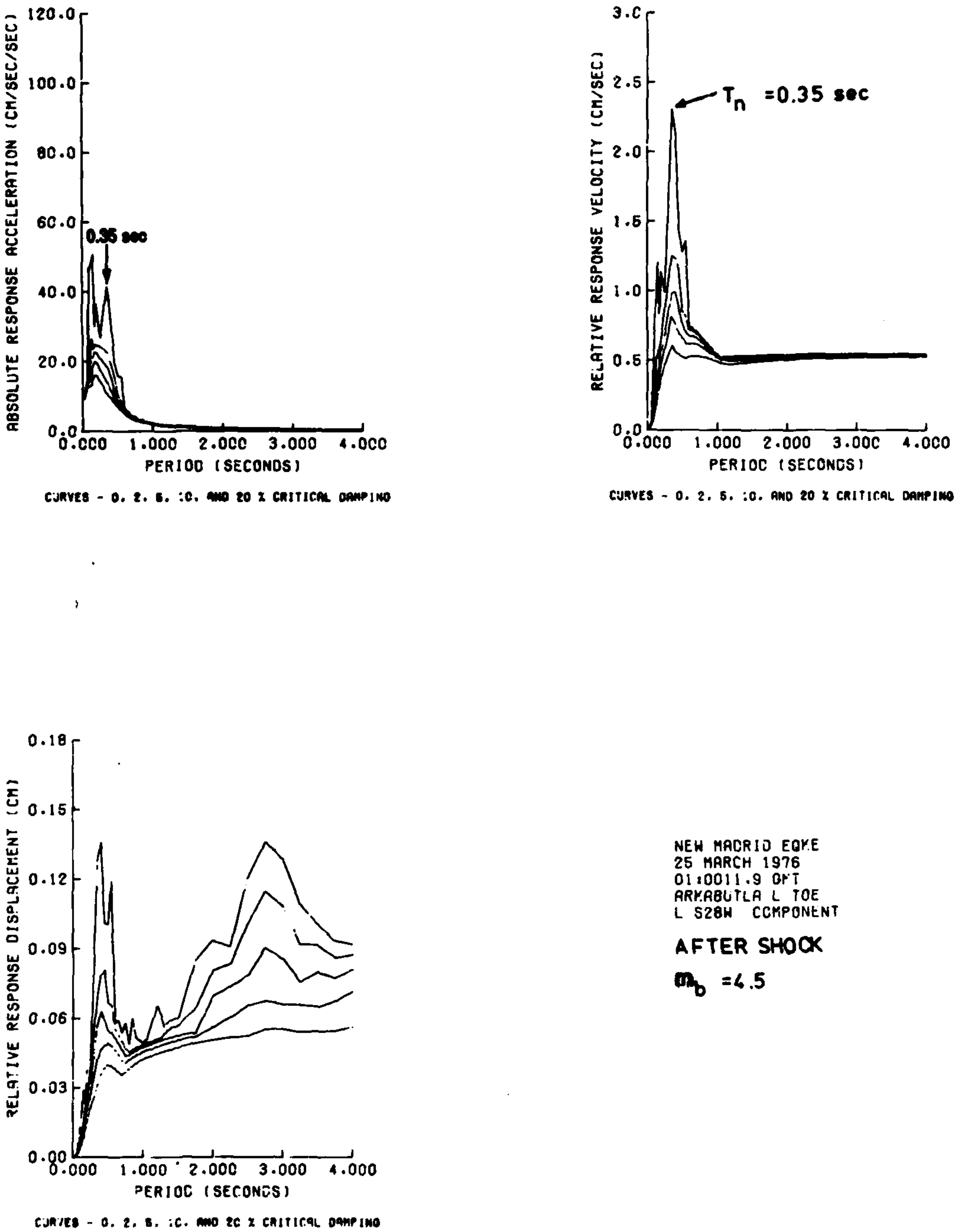


Figure 13. Response spectra of L-component of the aftershock at the toe of Arkabutla Dam

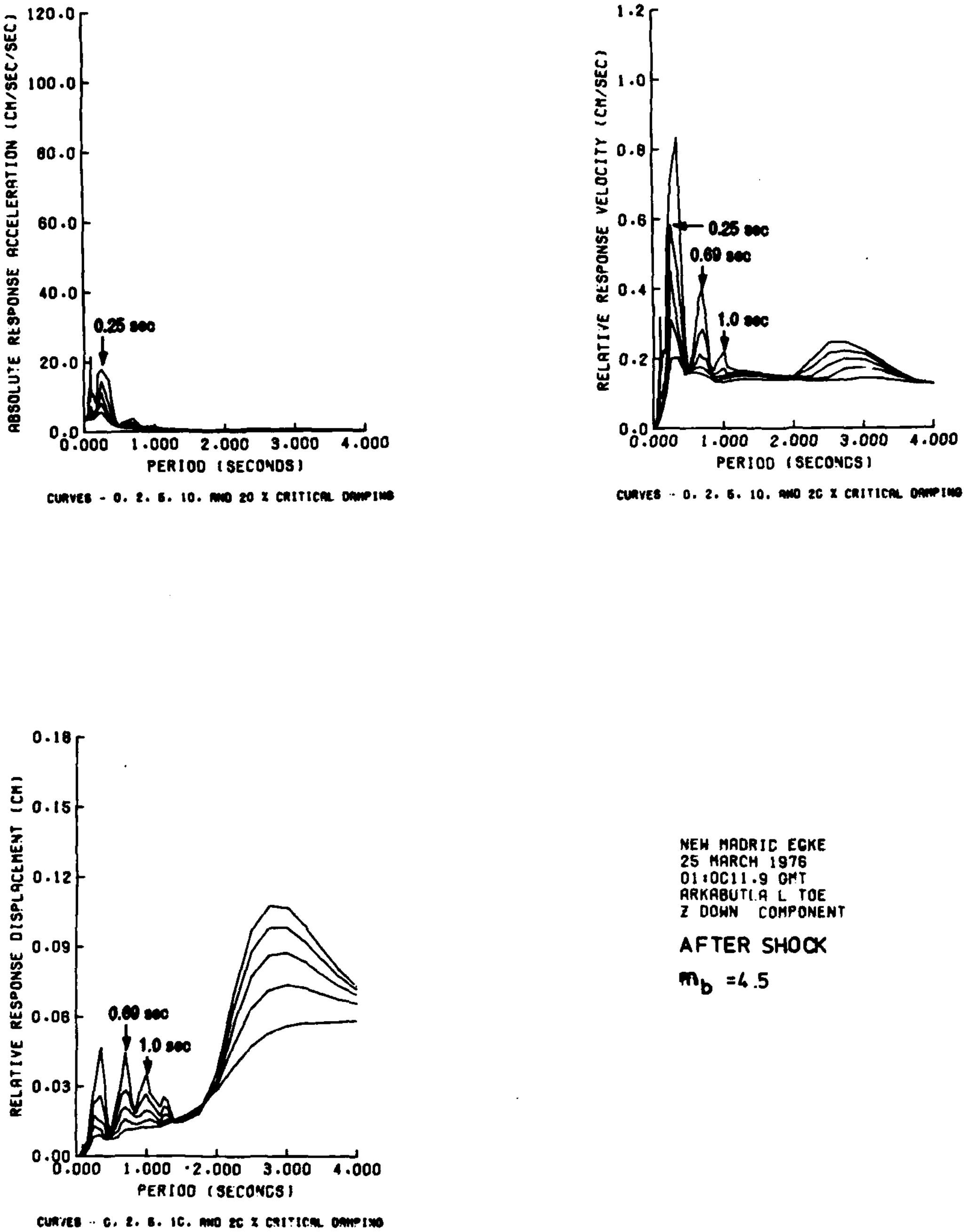


Figure 14. Response spectra of Z-component of the aftershock at the toe of Arkabutla Dam

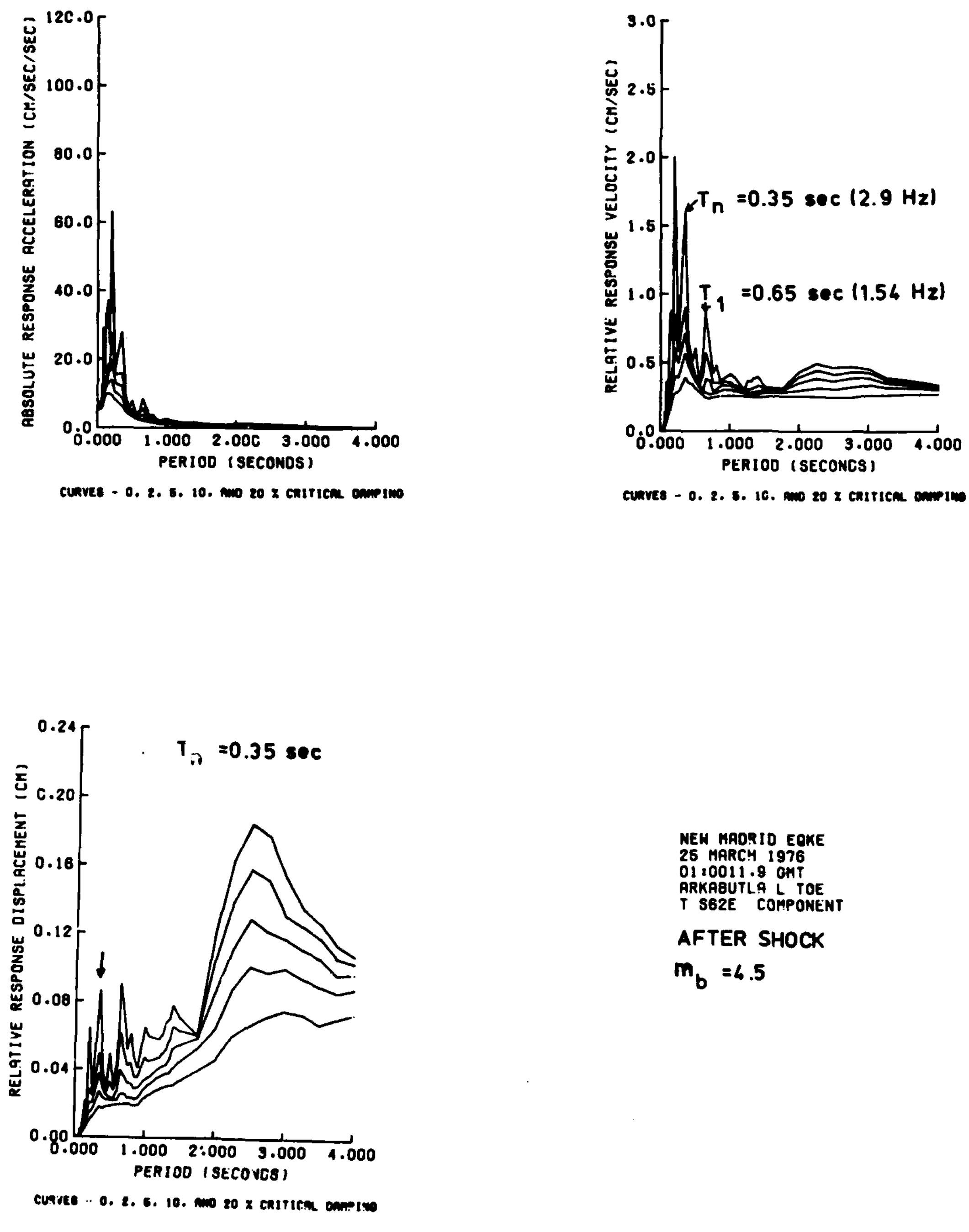


Figure 15. Response spectra of T-component of the aftershock at the toe of Arkabutla Dam

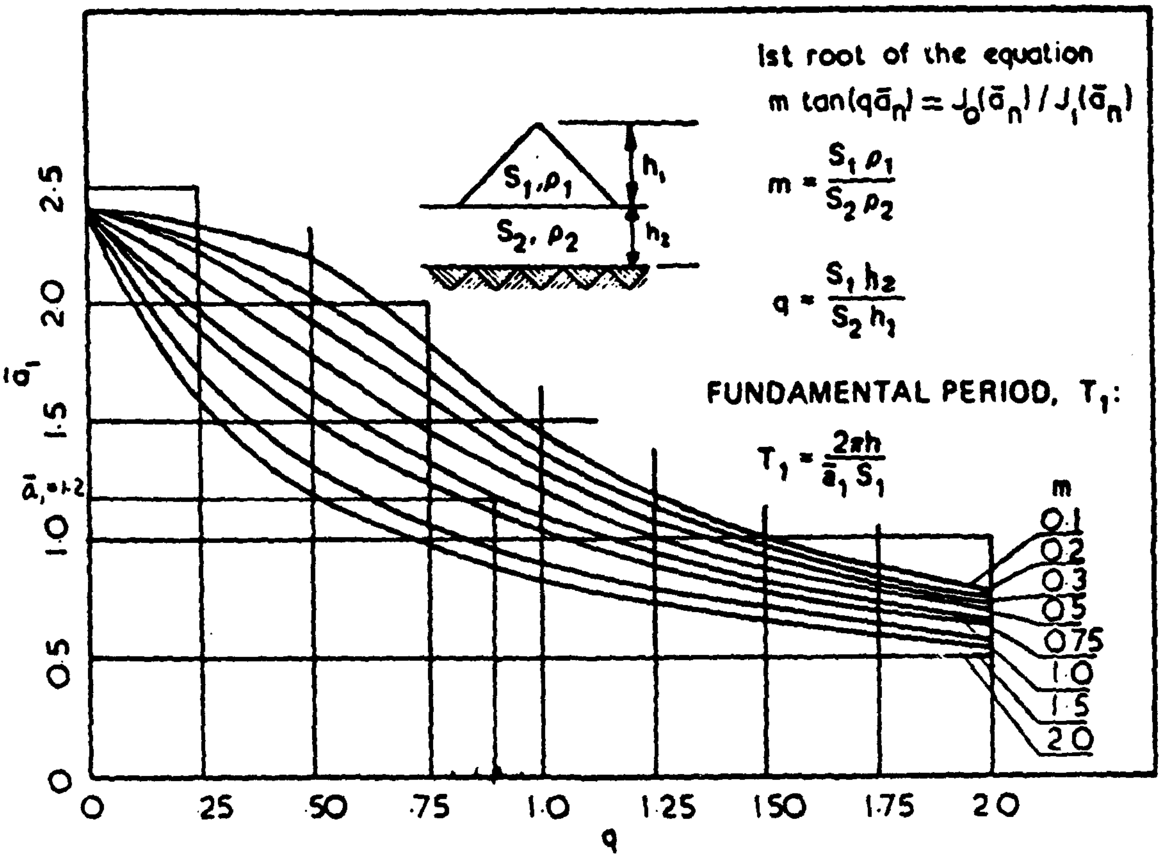


Figure 16. Fundamental period of dam-foundation system (after Sarma)

APPENDIX A: CORRECTED ACCELERATION, VELOCITY, AND DISPLACEMENT RECORDS OF ARKABUTLA DAM, MS (after Herrmann 1977)

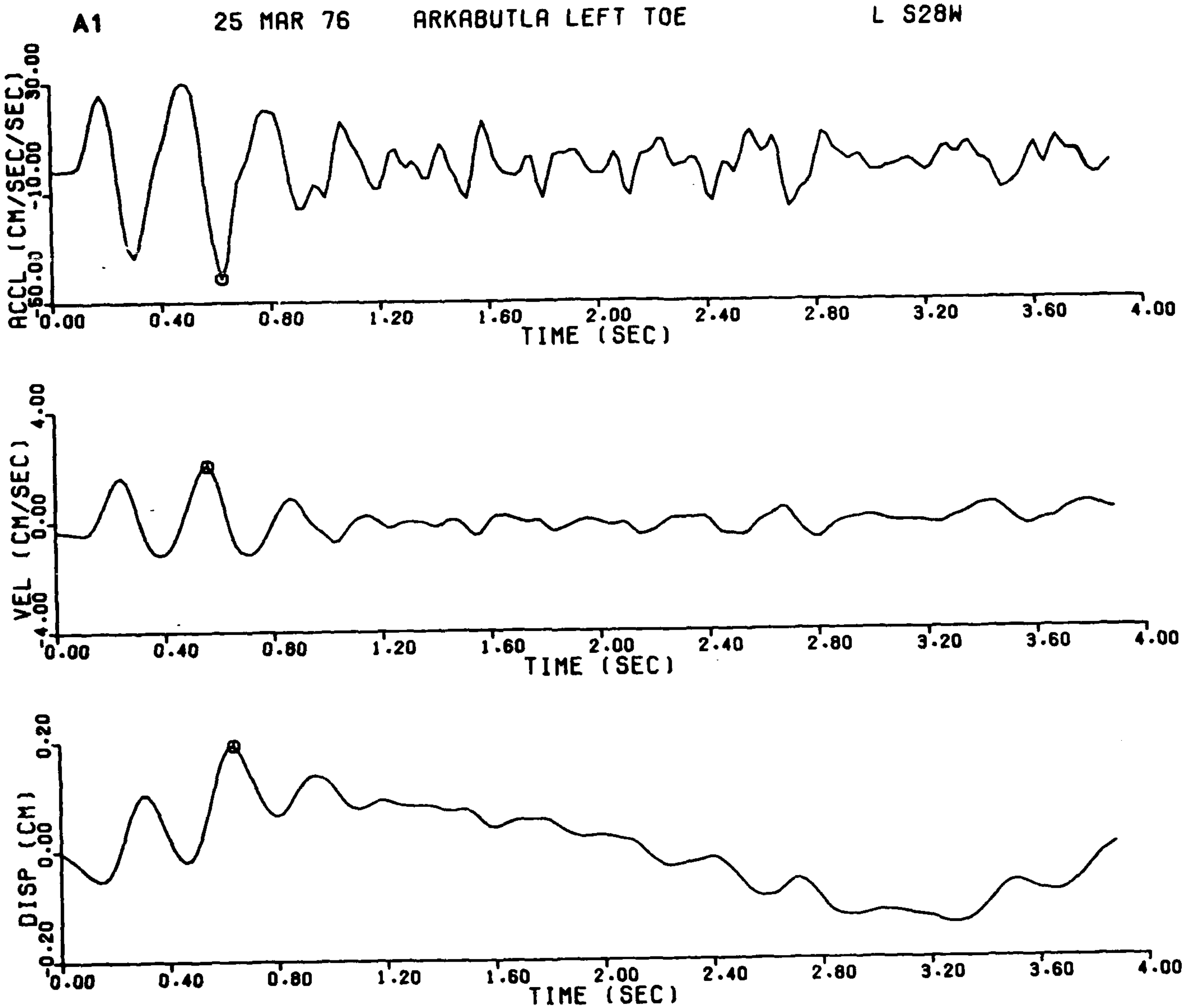


Figure A1. Corrected acceleration, velocity, and displacement records of L-component at left toe

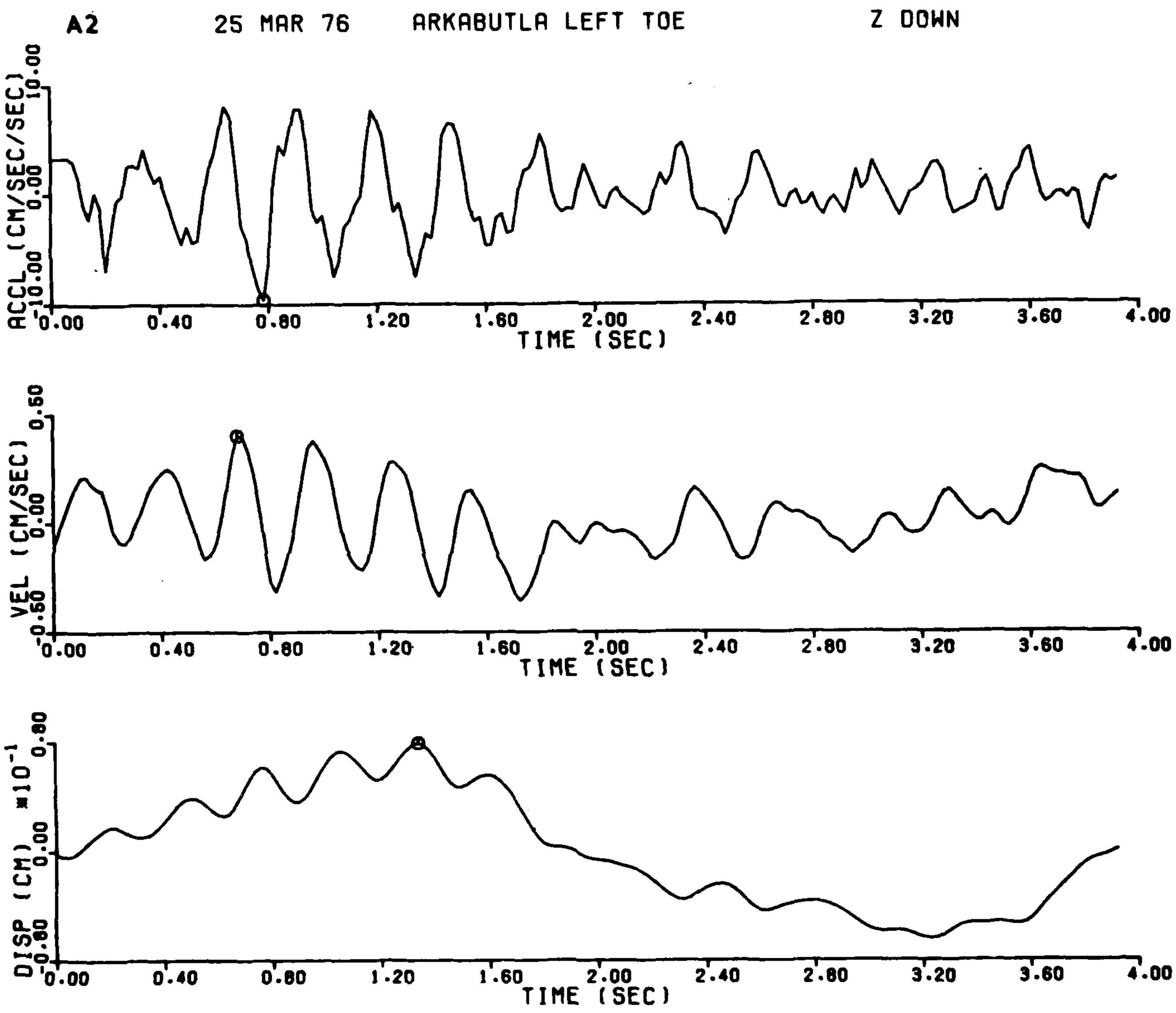


Figure A2. Corrected acceleration, velocity, and displacement records of Z-component at left toe

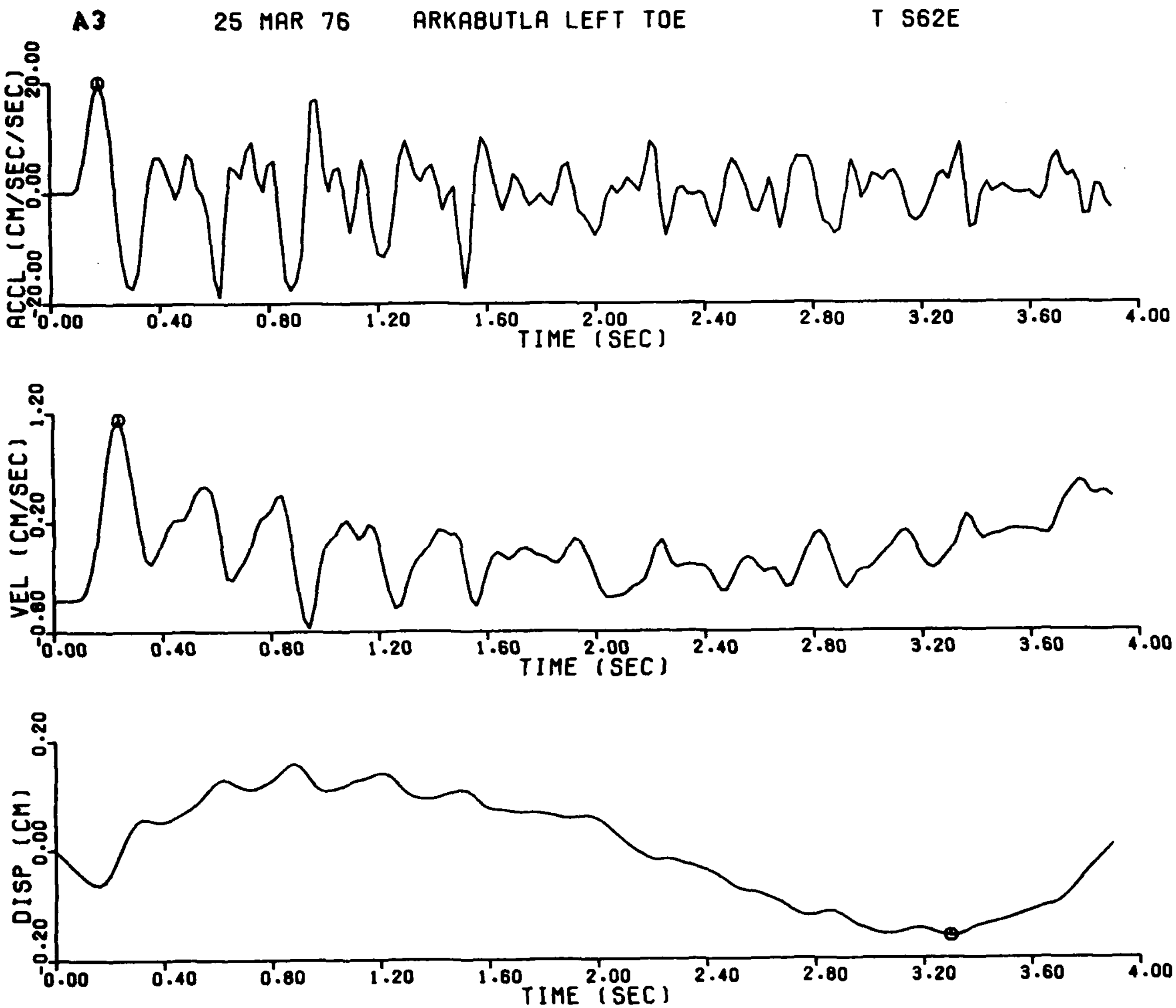


Figure A3. Corrected acceleration, velocity, and displacement records of T-component at left toe

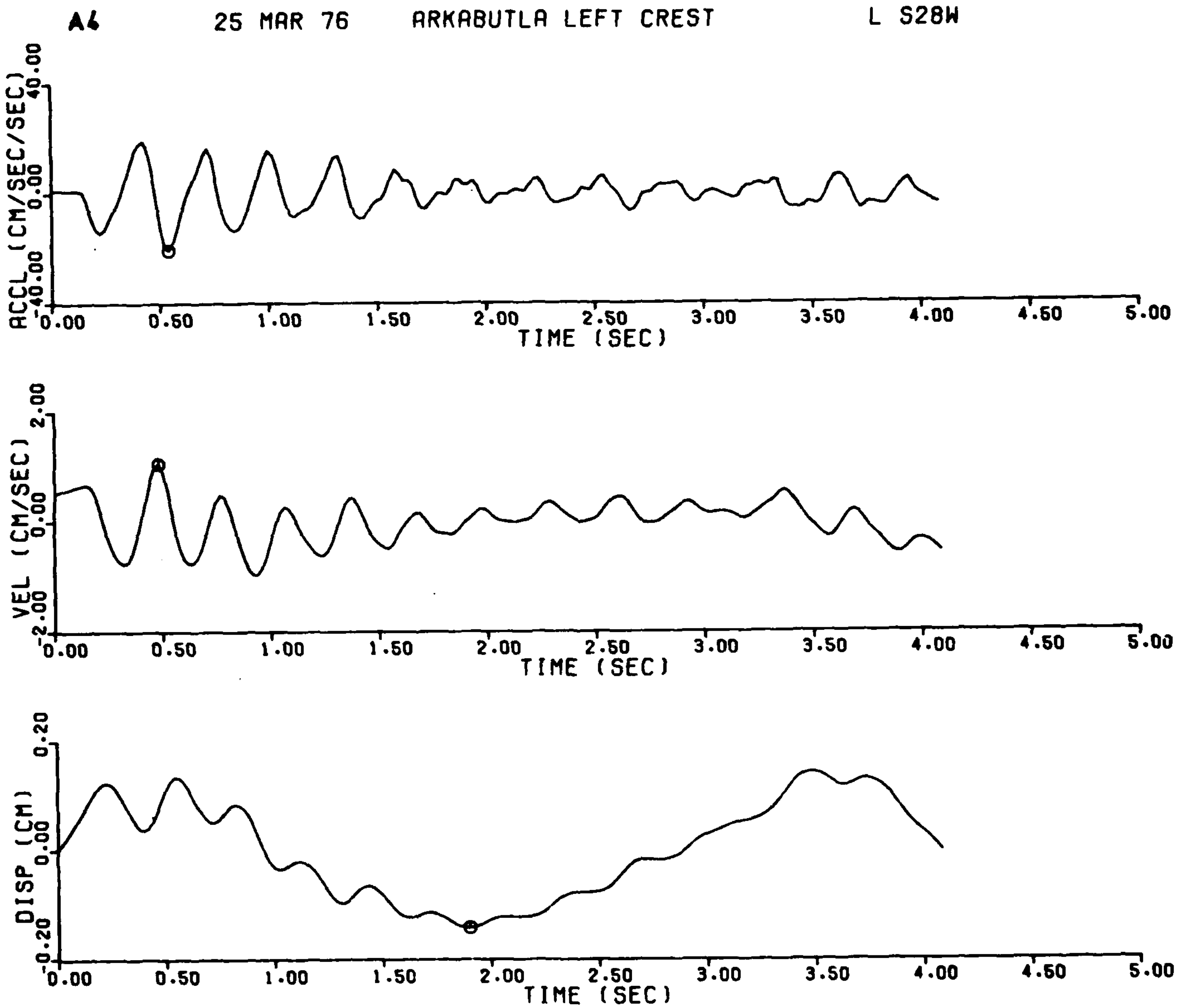


Figure A4. Corrected acceleration, velocity, and displacement records of L-component at left crest

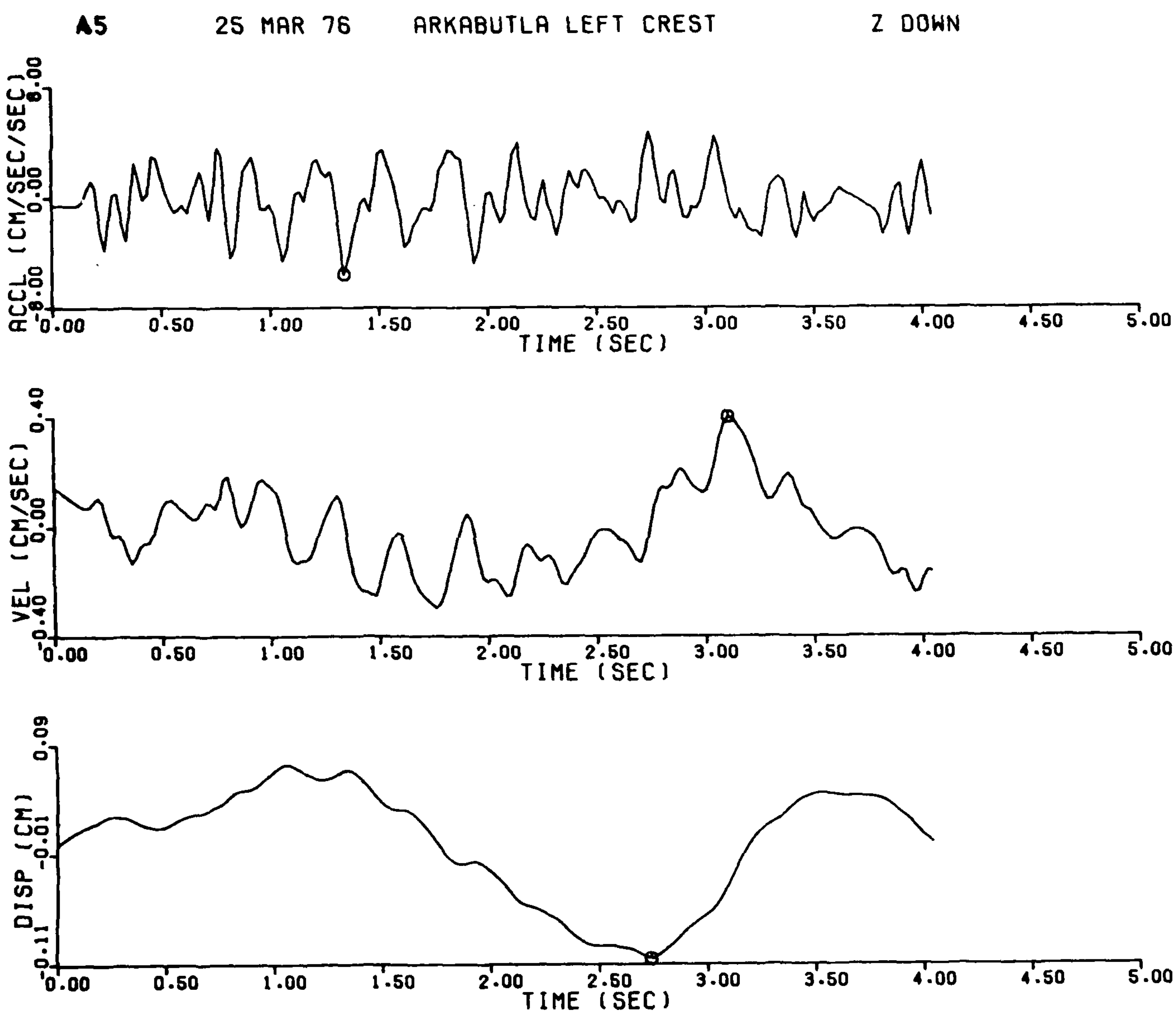


Figure A5. Corrected acceleration, velocity, and displacement records of Z-component at left crest

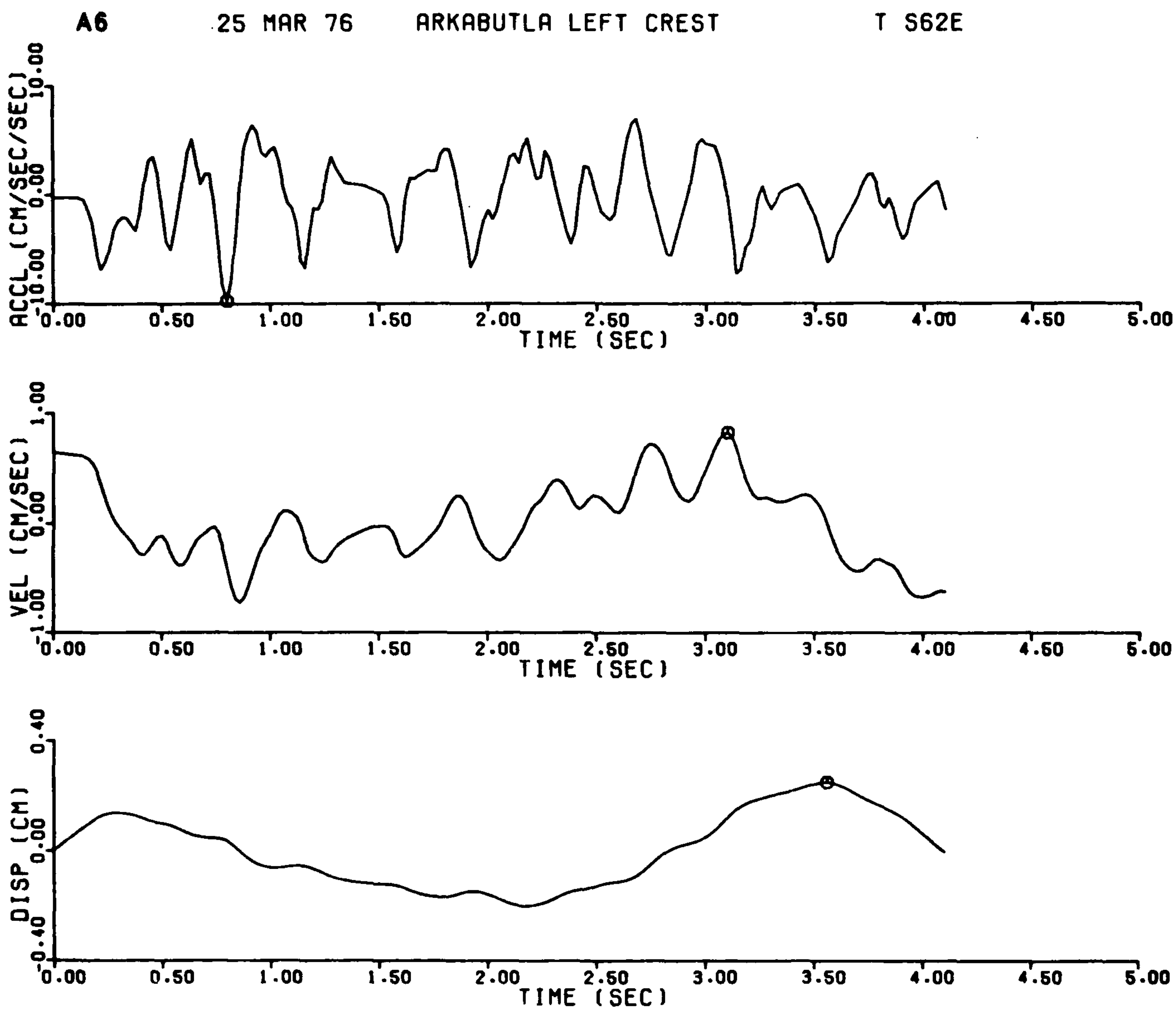


Figure A6. Corrected acceleration, velocity, and displacement records of T-component at left crest

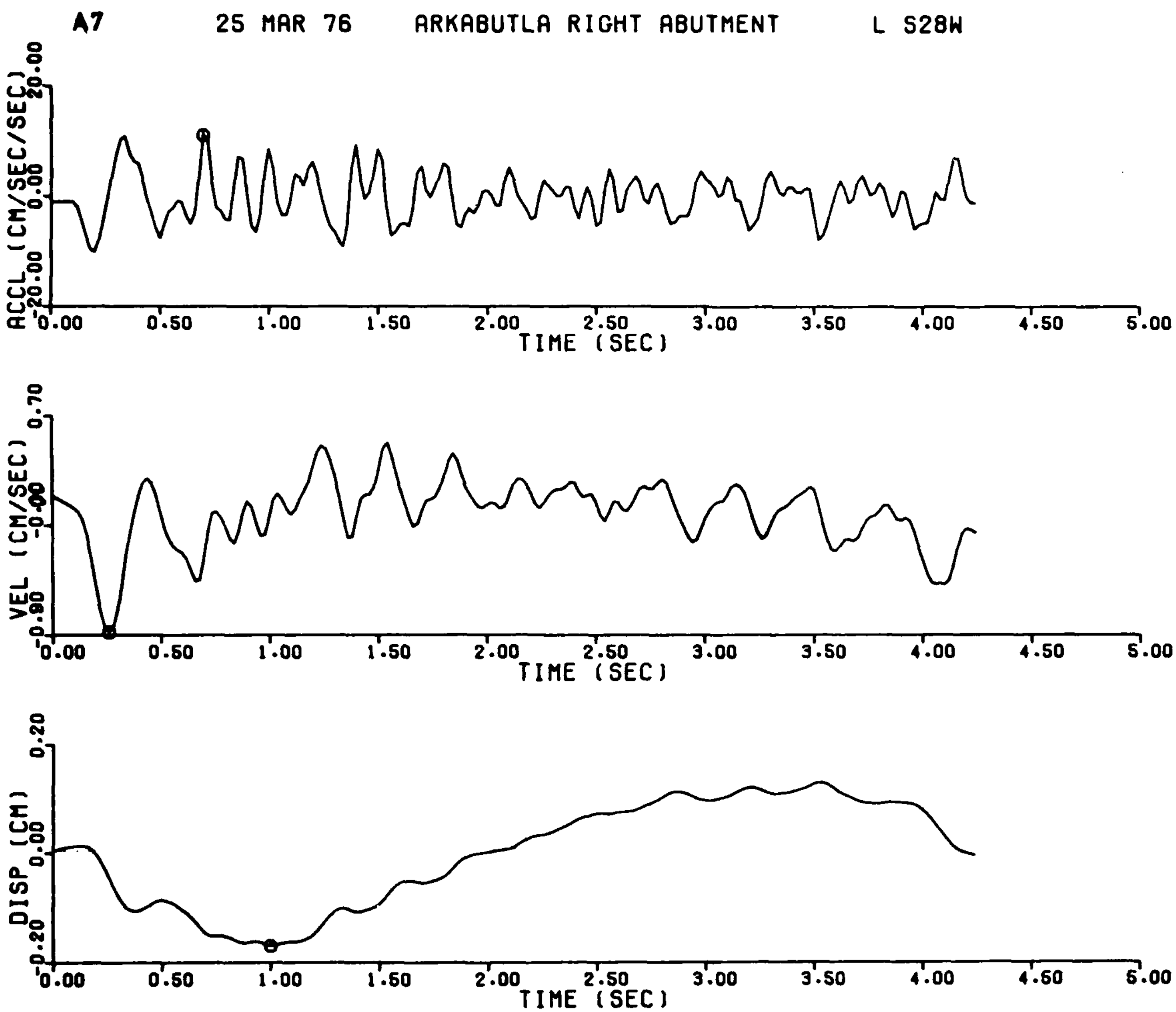


Figure A7. Corrected acceleration, velocity, and displacement records of L-component at right abutment

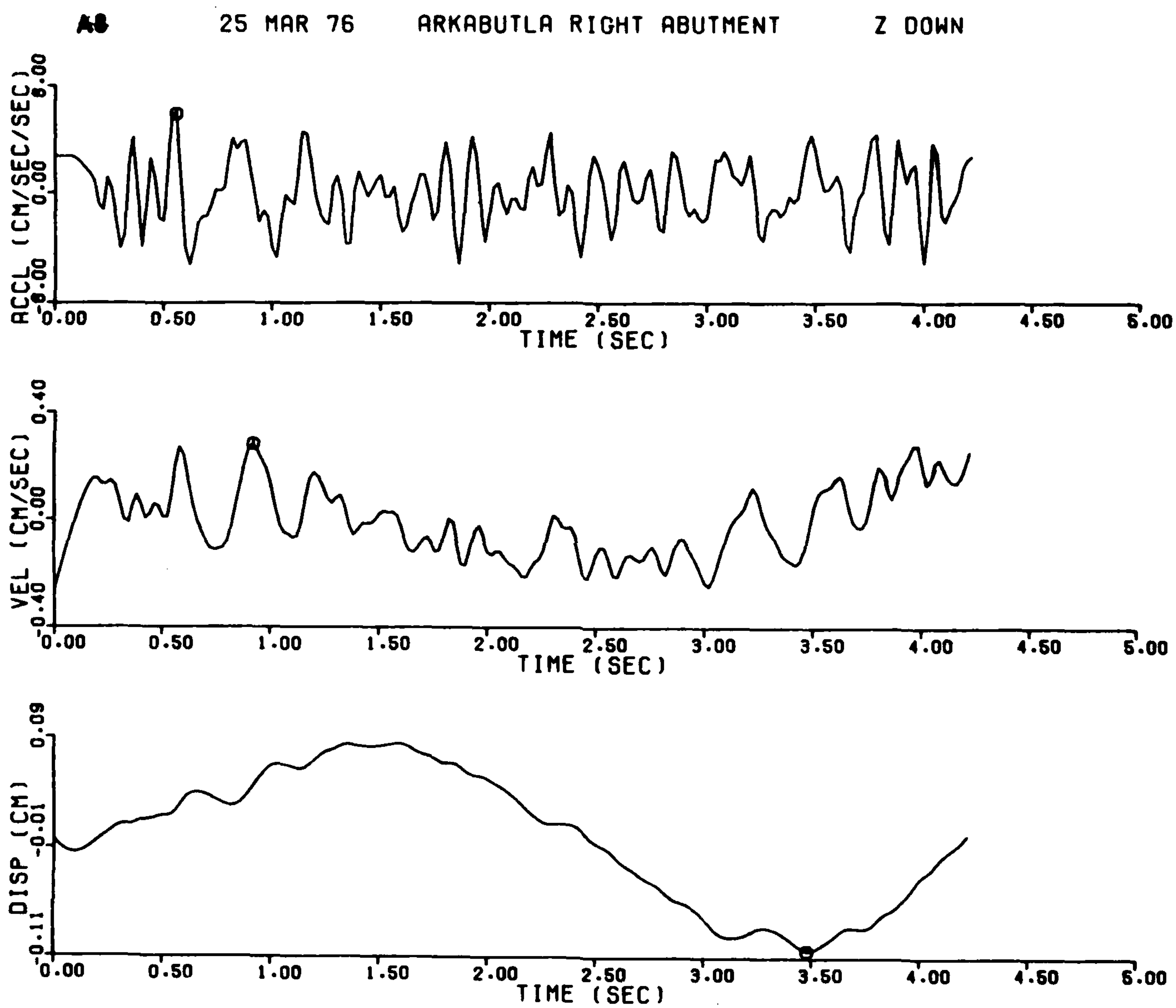


Figure A8. Corrected acceleration, velocity, and displacement records of Z-component at right abutment

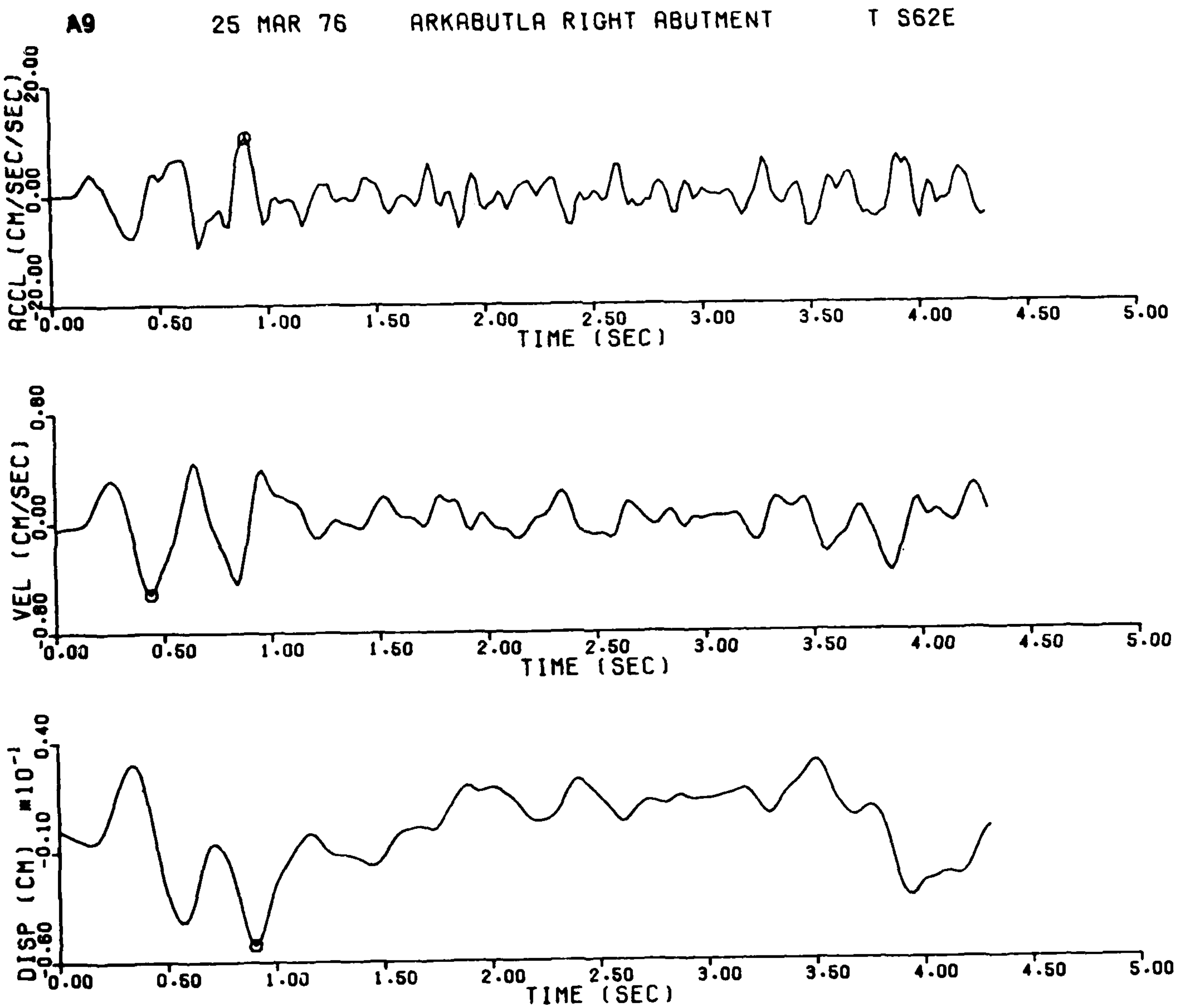


Figure A9. Corrected acceleration, velocity, and displacement records of L-component at right abutment

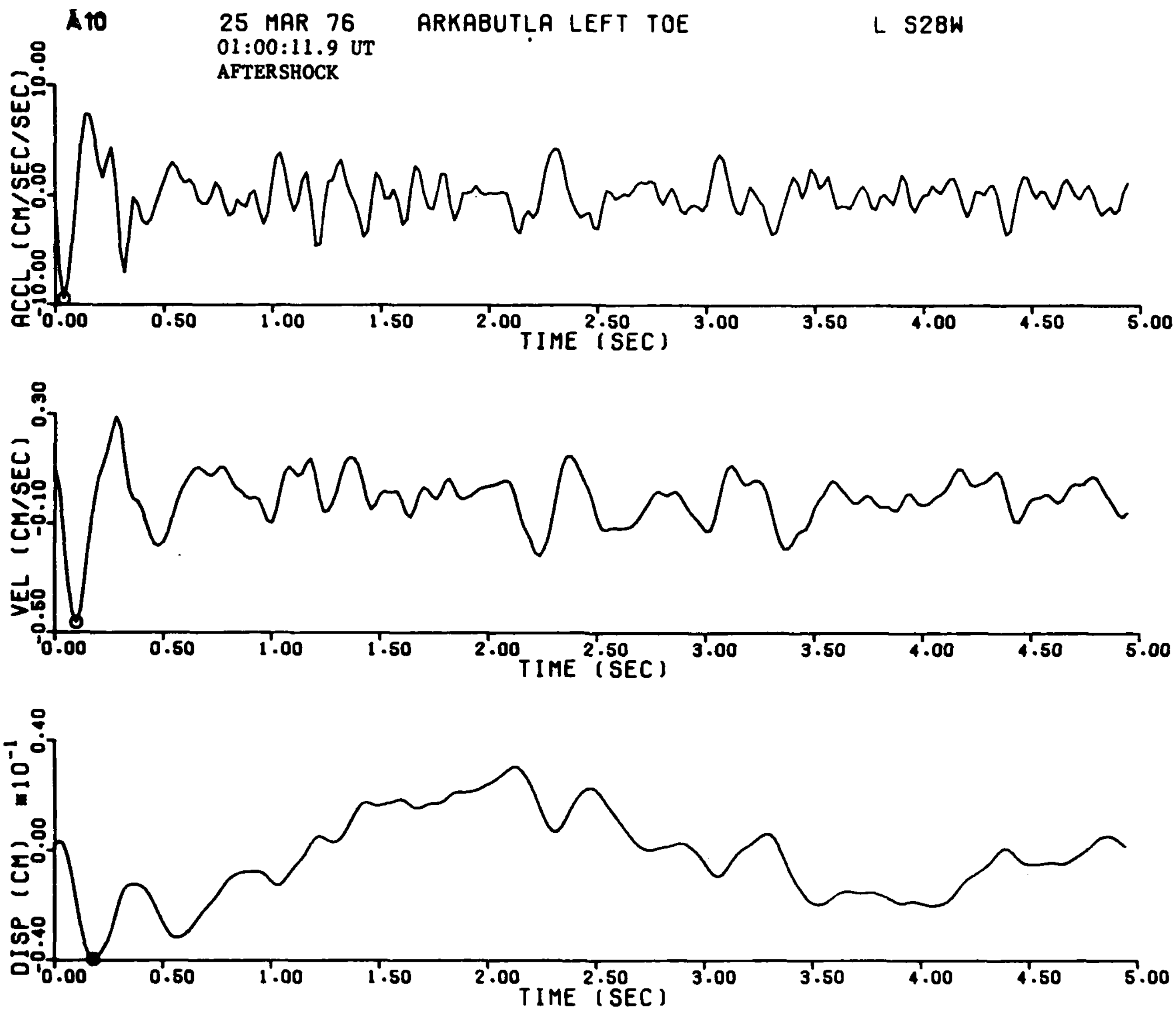


Figure A10. Corrected acceleration, velocity, and displacement records of L-component at left toe (aftershock)

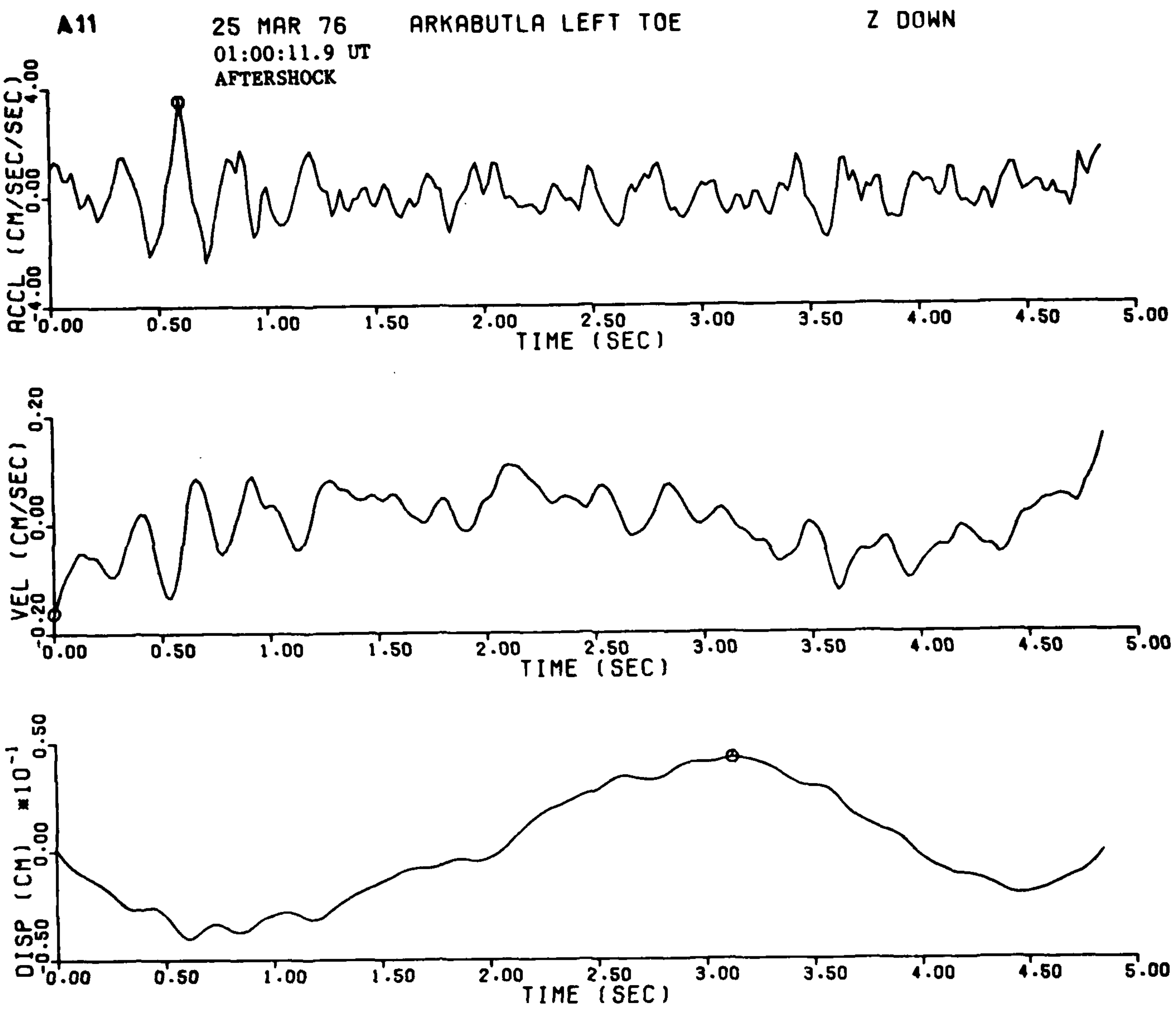


Figure A11. Corrected acceleration, velocity, and displacement records of Z-component at left toe (aftershock)

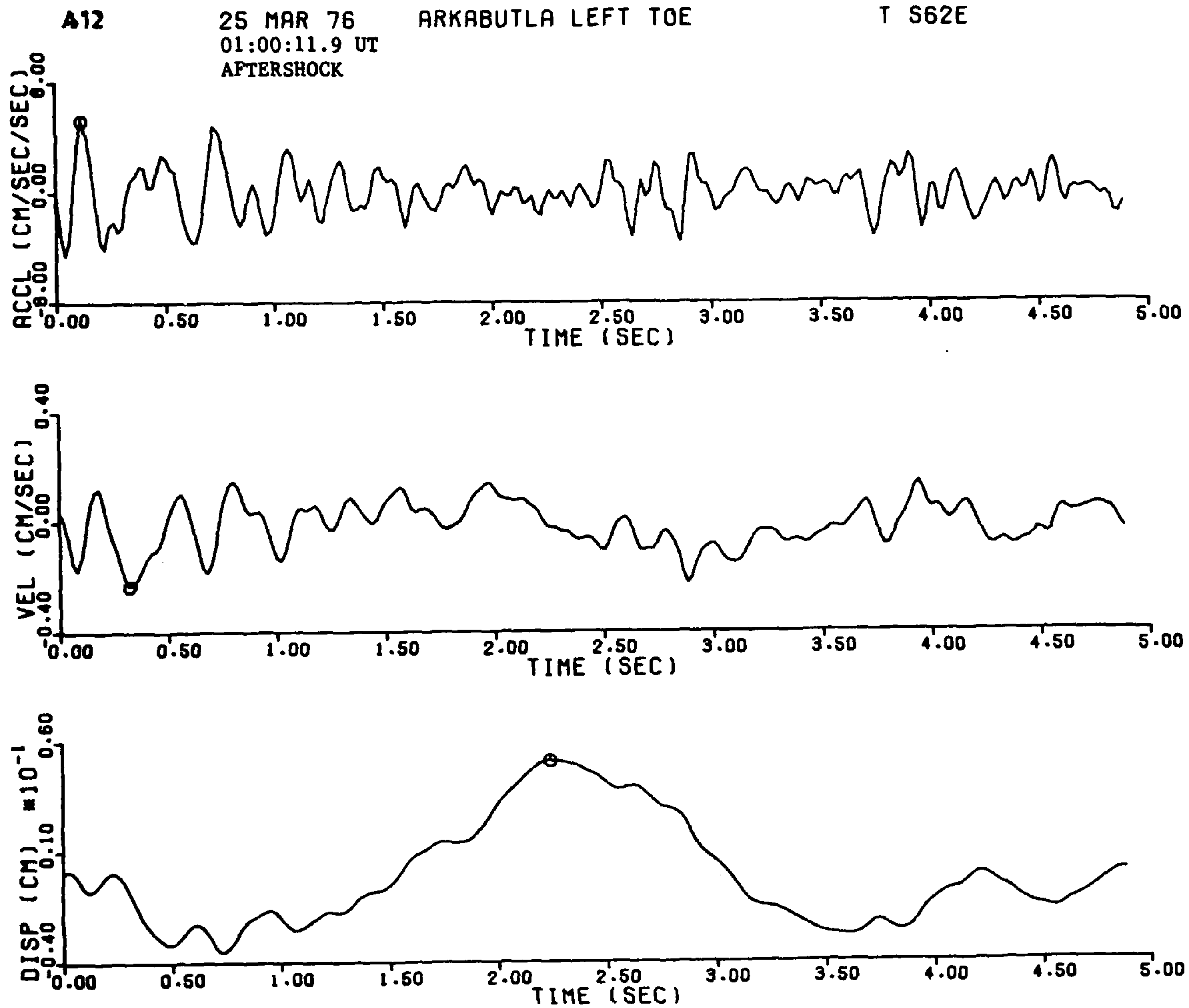
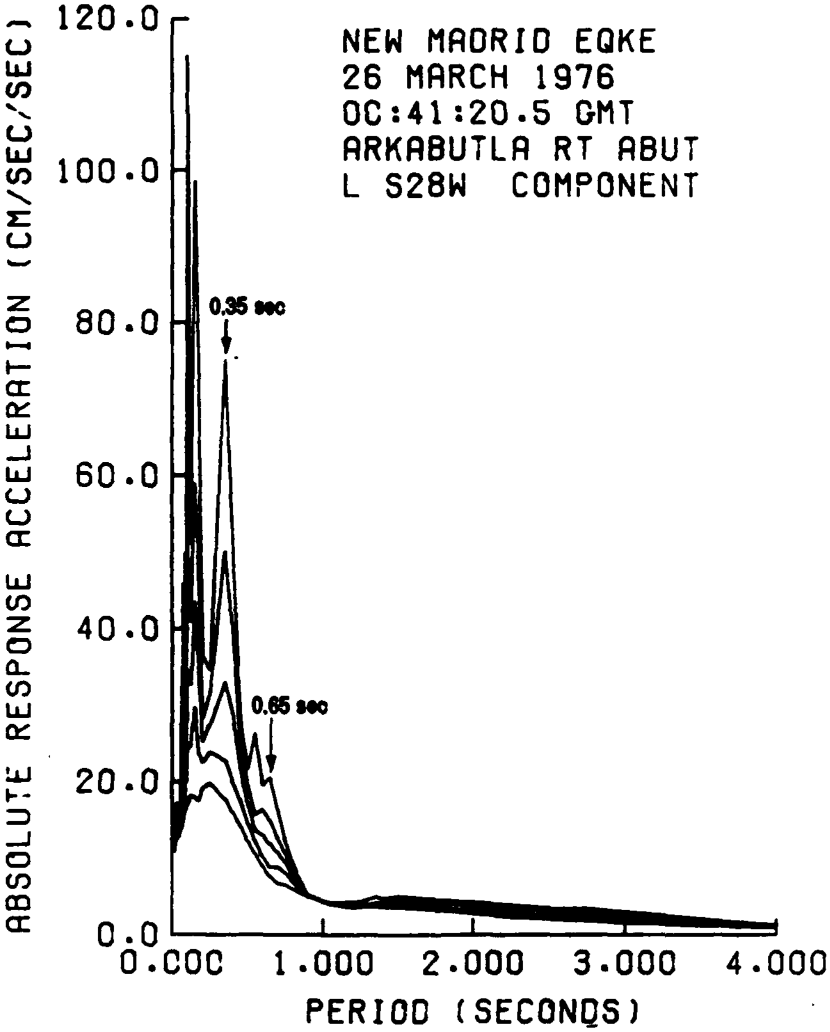


Figure A12. Corrected acceleration, velocity, and displacement records of T-component at left toe (aftershock)

APPENDIX B: THE RESPONSE SPECTRA OF THE L-COMPONENT FROM AN UNEQUAL TIME INTERVAL OF THE ACCELEROGRAM AT THE RIGHT ABUTMENT

The response spectra of the L-component at the right abutment were calculated from the digitized data with an unequal interval. Differences between equal and unequal interval digitized data can be found on the spectral amplitude and the spectral shape of the relative velocity. Specifically, the two frequencies of 1.54 Hz (0.65 sec) and 0.66 Hz (1.5 sec) are shown in Figures B-1 through B-3 but not in Figure 10.



CURVES - 0, 2, 5, 10, AND 20 % CRITICAL DAMPING

Figure B1. Absolute acceleration response spectra of 0, 2, 5, 10, and 20 percent critical damping, L-component at right abutment, Arkabutla Dam, MS

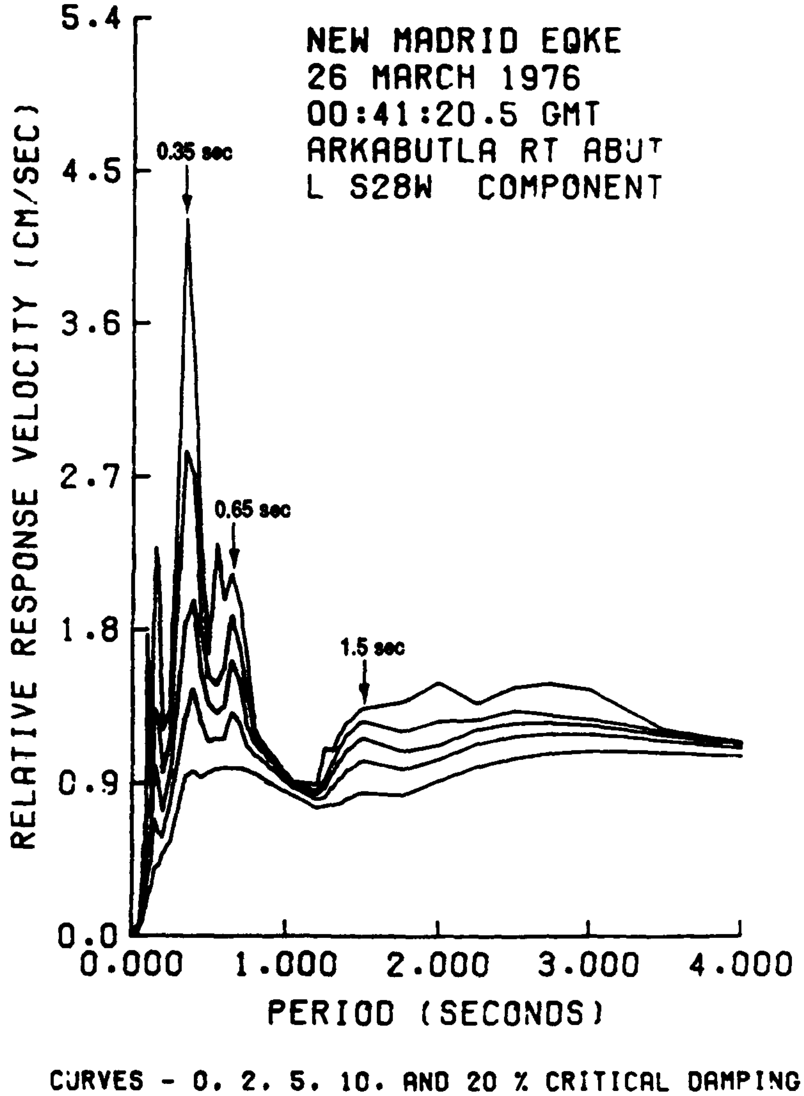


Figure B2. Relative velocity response spectra of 0, 2, 5, 10, and 20 percent critical damping, L-component at right abutment, Arkabutla, MS

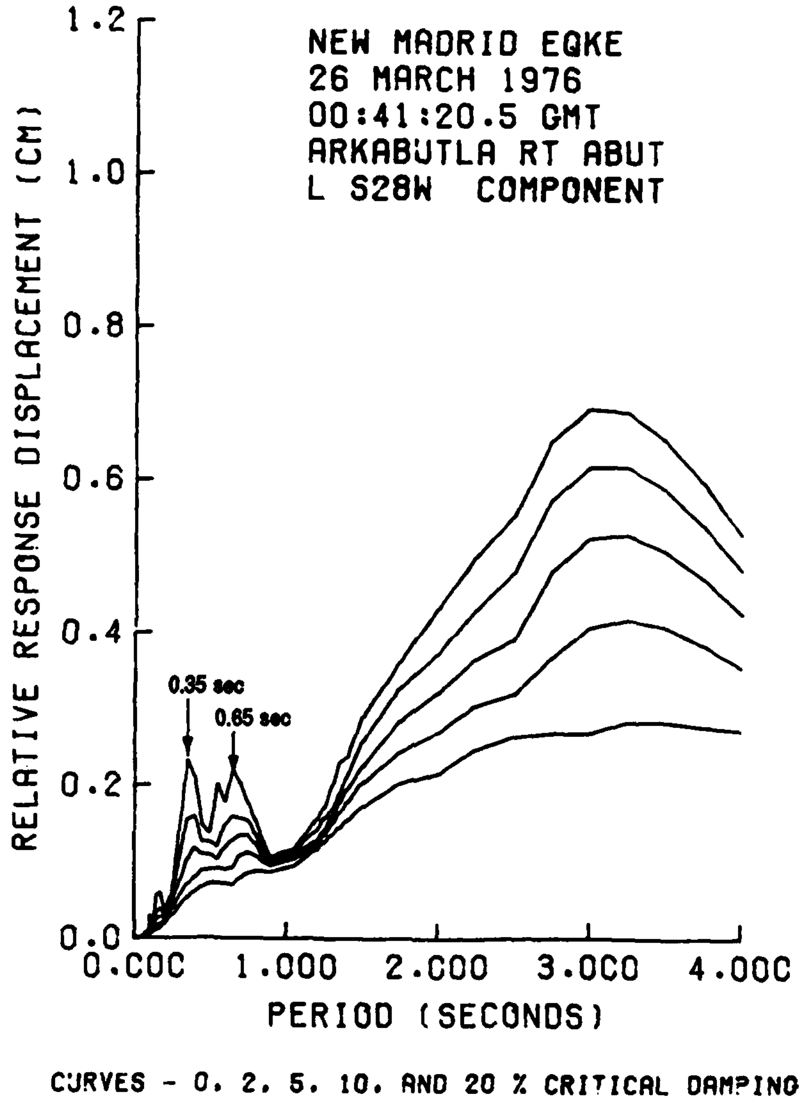


Figure B3. Relative displacement response spectra of 0, 2, 5, 10, and 20 percent critical damping, L-component at right abutment, Arkabutla Dam, MS